



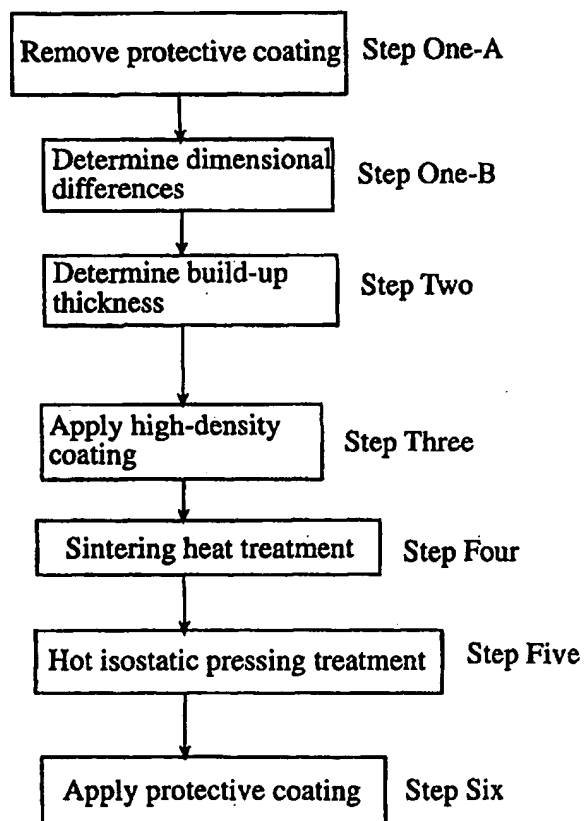
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(54) Title: METHODS FOR REPAIRING AND RECLASSIFYING GAS TURBINE ENGINE AIRFOIL PARTS

(57) Abstract

A method for repairing gas turbine engine airfoil parts. The dimensional differences between pre-repaired dimensions of a turbine engine airfoil part and desired post-repair dimensions of the turbine engine airfoil part are determined. A build-up thickness of coating material required to obtain the desired post-repair dimensions of the turbine engine airfoil part is determined. A high-density coating process, such as HVOF, is used to coat the turbine engine airfoil part with a coating material to the determined build-up thickness of coating material effective to obtain the desired post-repair dimensions after performing a sintering heat treatment and a hot isostatic pressing treatment, and, if performed, a re-application of a protective coating. The coating material comprises a metal alloy capable of forming a diffusion bond with the substrate of the turbine engine airfoil part. After the coating material is applied, the sintering heat treatment process is performed to prevent gas entrapment of the coating material and/or the diffusion bonding area during the hot isostatic pressing process. Then, the hot isostatic pressing process is performed to obtain a post-repair turbine engine airfoil part having the desired post-repair dimensions and having diffusion bonding between the coating material and the turbine engine airfoil substrate. A protective coating may be first removed from the turbine engine airfoil part prior to performing the high-density coating process. Typically, this protective coating is present on an airfoil part to protect it from the hot corrosive environment it experiences during service. After performing the hot isostatic pressing process, the protective coating may be re-applied. In this case, the build-up thickness may determine to take into consideration the additional thickness of the post-repaired part due to the addition of the protective coating.



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METHODS FOR REPAIRING AND RECLASSIFYING GAS TURBINE ENGINE AIRFOIL PARTS

BACKGROUND OF THE INVENTION

The present invention pertains to a method for repairing gas turbine engine airfoil parts. More particularly, the present invention pertains to a method for restoring critical gas path flow area dimensions in cast nickel or cobalt-base superalloy airfoil components of a gas turbine engine.

Airfoil parts, such as blades and vanes, are critical components in the gas turbine engines that are used to power jet aircraft or for the generation of electricity. Each airfoil part is an individual unit having a root or attachment section and an airfoil section. The airfoil section has specific chordal and length dimensions that define the airfoil characteristics of the part. The root section is engaged with and held by a housing member. A plurality of the airfoil parts are thus assembled with the housing member to form a disc or ring. Blades, which during operation are rotating part, are assembled into and disc. Vane, which remain stationary, are assembled into a nozzle or vane ring. In the operating gas turbine engine the assembled rings and discs, determine the path of the intake, combustion and exhaust gasses that flow through the engine.

The airfoil part may be either a rotating component or a non-rotating component of the gas turbine engine. If the part is a rotating component, during operation of the turbine engine the part is subjected to centrifugal forces that exert deforming stresses. These deforming stresses cause creep rupture and fatigue problems that can result in the failure of the part. Non-rotating components, such as vanes, are not subjected to centrifugal forces that exert deforming stresses. However, like the rotating parts,

1 these parts are subjected to other deformation such as from hot gas erosion and/or
2 foreign particle strikes. This deformation results in the alteration of the dimensions of
3 the airfoil section. The alteration of the dimensions of the airfoil section can
4 detrimentally modify the airflow through the gas turbine engine which is critical to
5 the engine's performance.

6

7 An example of a non-rotating airfoil part is the 2nd stage vane of the Pratt & Whitney
8 JT8D model 1 through 17R gas turbine engine. This part is manufactured by the "lost
9 wax" or "investment casting" process. The vane is cast from one of several highly
10 alloyed nickel or cobalt-base materials. As a new part in a new gas turbine engine, or
11 as a new spare part in an overhauled engine, it begins its life cycle with a protective
12 diffusion coating on its airfoil surfaces and a wear coating on surfaces known to have
13 excessive wear patterns.

14

15 When the gas turbine engine is operating, the vane will see temperatures of about
16 1500 degree F. Since the vane does not rotate and thus is not subject to creep rupture,
17 its demise is most often influenced by the number of times it is repaired. The reason
18 for this is the repair process itself.

19

20 The repair process consists of the following operations:

- 21 1). degrease, wash to remove engine carbon, etc.
- 22 2.) grit blast to remove wear coatings, and any sulfidation which is present
- 23 3.) chemically remove the diffusion coating
- 24 4.) blend to remove nicks, dents, etc.
- 25 5.) weld, grind, polish etc.

26

1 The repair operations that remove metal by chemical stripping, grit blasting, blending
2 and polishing shorten the life cycle of the vane. The coating removal is a major
3 contributor because it is diffused into the parent metal. When certain minimum airfoil
4 dimensions cannot be met the part is deemed non-repairable and must be retired from
5 service. Thus, there is a need for a method for repairing gas turbine engine airfoil
6 parts that effectively and efficiently restores the airfoil dimensions of the part.

7
8 On another front, during the manufacture of metal components a coating operation is
9 performed to provide a coating material layer on the surface of a component substrate.
10 The coating material layer is formed to build-up the metal component to desired
11 finished dimensions and to provide the finished product with various surface
12 attributes. For example, an oxide layer may be formed to provide a smooth, corrosion
13 resistant surface. Also, a wear resistant coating, such as Carbide, Cobalt, or TiN is
14 often formed on cutting tools to provide wear resistance.

15
16 Chemical Vapor Deposition is typically used to deposit a thin film wear resistant
17 coating on a cutting tool substrate. For example, to increase the service life of a drill
18 bit, chemical vapor deposition can be used to form a wear resistant coating of Cobalt
19 on a high speed steel (HSS) cutting tool substrate. The bond between the substrate and
20 coating occurs primarily through mechanical adhesion within a narrow bonding
21 interface. During use, the coating at the cutting surface of the cutting tool is subjected
22 to shearing forces resulting in flaking of the coating off the tool substrate. The failure
23 is likely to occur at the narrow bonding interface.

24
25 Figure 12(a) is a side view of a prior art tool bit coated with a wear resistant coating.
26 In this case, the wear resistant coating may be applied by the Chemical Vapor
27 Deposition method so that the entire tool bit substrate receives an even thin film of a

1 relatively hard material, such as Carbide, Cobalt or TiN. Since the coating adheres to
2 the tool bit substrate mostly via a mechanical bond located at a boundary interface,
3 flaking and chipping off the coating off of the substrate is likely to occur during use,
4 limiting the service life of the tool bit. Figure 12(b) is a side view of a prior art tool
5 bit having a fixed wear resistant cutting tip. In this case, a relatively hard metal
6 cutting tip is fixed to the relatively soft tool bit substrate. The metal cutting tip, which
7 is typically comprised of a Carbide or Cobalt alloy, is fixed to the tool bit substrate by
8 brazing. During extended use the tool bit is likely to fail at the relatively brittle
9 brazed interface between the metal cutting tip and the tool substrate, and again, the
10 useful service life of the tool bit is limited.

11
12 Another coating method, known as Conventional Plasma Spray uses a super heated
13 inert gas to generate a plasma. Powder feedstock is introduced and carried to the
14 workpiece by the plasma stream. Conventional plasma spray coating methods deposit
15 the coating material at relatively low velocity, resulting in voids being formed within
16 the coating and in a coating density typically having a porosity of about 5.0%. Again,
17 the bond between the substrate and the coating occurs primarily through mechanical
18 adhesion at a bonding interface, and if the coating is subjected to sufficient shearing
19 forces it will flake off of the workpiece substrate.

20
21 Another coating method, known as the Hyper Velocity Oxyfuel (HVOF) plasma
22 thermal spray process is used to produce coatings that are nearly absent of voids. In
23 fact, coatings can be produced nearly 100% dense, with a porosity of less than 0.5%.
24 In HVOF thermal spraying, a fuel gas and oxygen are used to create a combustion
25 flame at 2500 to 3100°C. The combustion takes place at a very high chamber
26 pressure and a supersonic gas stream forces the coating material through a small-
27 diameter barrel at very high particle velocities. The HVOF process results in

1 extremely dense, well-bonded coatings. Typically, HVOF coatings can be formed
2 nearly 100% dense, with a porosity of <0.5%. The high particle velocities obtained
3 using the HVOF process results in relatively better bonding between the coating
4 material and the substrate, as compared with other coating methods such as the
5 Conventional Plasma spray method or the Chemical Vapor Deposition method.
6 However, the HVOF process also forms a bond between the coating material and the
7 substrate that occurs primarily through mechanical adhesion at a bonding interface.

8
9 Detonation Gun coating is another method that produces a relatively dense coating.
10 Suspended powder is fed into a long tube along with oxygen and fuel gas. The
11 mixture is ignited in a controlled explosion. High temperature and pressure is thus
12 created to blast particles out of the end of the tube and toward the substrate to be
13 coated.

14
15 An example of using HVOF or Detonation Gun coating techniques is disclosed in US
16 Patent No. 5,584,663, issued to Schell. This reference discloses that the tips of
17 turbine blades can be formed by melting and fusing a powder alloy. Preferably, the
18 blade tip is generated by depositing molten metal alloy powder in multiple passes.
19 Squealers at the perimeter of the blade tip may be formed using methods such as
20 Detonation Gun or HVOF spray methods. The forming step may be used to generate
21 a near-net shaped blade tip, and a subsequent machining step may be employed to
22 generate the final or preferred shape of the blade tip.

23
24 Casting is a known method for forming metal components. Typically, a substrate
25 blank is cast to near-finished dimensions. Various machining operations, such as
26 cutting, sanding and polishing are performed on the cast substrate blank to eventually
27 obtain the metal component at desired finished dimensions. A cast metal component

1 will typically have a number of imperfections caused by voids and contaminants in
2 the cast surface structure. The imperfections may be removed by machining away the
3 surface layer of the component, and/or by applying a surface coating.

4
5 The manufacture of metal components often entails costly operations to produce
6 products with the desired surface texture, material properties and dimensional
7 tolerances. For example, a known process for manufacturing a metal component
8 requires, among other steps, making a casting of the metal component, treating the
9 metal component using a Hot Isostatic Pressing (HIP) treatment process, and then
10 machining the metal component to remove surface imperfections and obtain the
11 desired dimensional tolerances.

12
13 HIP treatment is used in the densification of cast metal components and as a diffusion
14 bonding technique for consolidating powder metals. In the HIP treatment process, a
15 part to be treated is raised to a high temperature and isostatic pressure. Typically, the
16 part is heated to 0.6 - 0.8 times the melting point of the material comprising the part,
17 and subjected to pressures on the order of 0.2 to 0.5 times the yield strength of the
18 material. Pressurization is achieved by pumping an inert gas, such as Argon, into a
19 pressure vessel. Within the pressure vessel is a high temperature furnace, which heats
20 the gas to the desired temperature. The temperature and pressure are held for a set
21 length of time, and then the gas is cooled and vented.

22
23 The HIP treatment process is used to produce near-net shaped components, reducing
24 or eliminating the need for subsequent machining operations. Further, by precise
25 control of the temperature, pressure and time of a HIP treatment schedule a particular
26 microstructure for the treated part can be obtained.

27

1 All casting processes must deal with problems that the wrought processes do not
2 encounter. Major among those are porosity and shrinkage that are minimized by
3 elaborate gating techniques and other methods that increase cost and sometimes lower
4 yield. However, the ability to produce a near-net or net shape is the motivating factor.
5 In some cases, it is more cost effective to intentionally cast the part not using
6 elaborate and costly gating techniques and HIP treat the part to eliminate the sub-
7 surface porosity. The surface of the part is then machined until the dense substrate is
8 reached.

9

10 US Patent No. 5,156,321, issued to Liburdi et al and US Patent No. 5,071,054, issued
11 to Dzugan et al. are examples of methods that employ the HIP treatment process.
12 Liburdi et al. discloses a technique to repair or join sections of a superalloy article. A
13 powder matching the superalloy composition is sintered in its solid state to form a
14 porous structure in an area to be repaired or joined. A layer of matching powder,
15 modified to incorporate melting point depressants, is added to the surface of the
16 sintered region. Liburdi discloses that the joint is raised to a temperature where the
17 modified layer melts while the sintered layer and base metal remain solid. The
18 modified material flows into the sintered layer by capillary action resulting in a dense
19 joint with properties approaching those of the base metal. This reference discloses
20 that HIPing can be used as part of the heat treatment to close any minor interior
21 defects. Dzugan et al. discloses fabricating a superalloy article by casting, and then
22 refurbishing primary defects in the surface of the cast piece. The defects are removed
23 by grinding. The affected portions of the surface are first filled with a material that is
24 the same composition as the cast article. Then, a cladding powder is applied to the
25 surface through the use of a binder coat to obtain a smooth surface. The article is then
26 heated to melt the cladding powder, and then cooled to solidify. Finally, the article is
27 HIPed to achieve final closure of the surface defects.

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Metal alloy components, such as gas turbine parts such as blades and vanes, are often damaged during use. During operation, gas turbine parts are subjected to considerable degradation from high pressure and centrifugal force in a hot corrosive atmosphere. The gas turbine parts also sustain considerable damage due to impacts from foreign particles. This degradation results in a limited service life for these parts. Since they are costly to produce, various repair methods are employed to refurbish damaged gas turbine blades and vanes.

Some examples of methods employed to repair gas turbine blades and vanes include US Patent No. 4,291,448, issued to Cretella et al.; US Patent No. 4,028,787, issued to Cretella et al.; US Patent No. 4,866,828, issued to Fraser; and US Patent No. 4,837,389, issued to Shankar et al.

Cretella '448 discloses a process to restore turbine blade shrouds that have lost their original dimensions due to wear while in service. This reference discloses using the known process of TIG welding worn portions of a part with a weld wire of similar chemistry as the part substrate, followed by finish grinding. The part is then plasma sprayed with a material of similar chemistry to a net shape requiring little or no finishing. The part is then sintered in an argon atmosphere. The plasma spray process used in accordance with Cretella '448 results in a coating porosity of about 5.0%. Even after sintering the coating remains attached to the substrate and weld material only be a mechanical bond at an interface bonding layer making the finished piece prone to chipping and flaking.

1 Cretella '787 discloses a process for restoring turbine vanes that have lost their
2 original dimensions due to wear while in service. Again, a conventional plasma spray
3 process is used to build up worn areas of the vane before performing a sintering
4 operation in a vacuum or hydrogen furnace. The porosity of the coating, and the
5 interface bonding layer, results in a structure that is prone to chipping and flaking.

6
7 Fraser discloses a process to repair steam turbine blades or vanes that utilize some
8 method of connecting them together (i.e. lacing wire). In accordance with the method
9 disclosed by Fraser, the area of a part that has been distressed is removed and a new
10 piece of like metal is welded to the part. The lacing holes of the part are plug welded.
11 The part is then subjected to hot striking to return it to its original contour, and the
12 lacing holes are re-drilled.

13
14 Shankar et al. disclose a process for repairing gas turbine blades that are distressed
15 due to engine operation. A low-pressure plasma spray coating is applied to the vanes
16 and the part is re-contoured by grinding. A coating of aluminum is then applied using
17 a diffusion coating process. Again, the conventional low-pressure plasma spray
18 process forms a mechanical bond at an interface boundary between the coating and
19 the substrate, resulting in a structure that is prone to failure due to chipping and
20 flaking.

21
22 Other examples of methods for repairing or improving the characteristics of turbine
23 engine airfoil parts include US 5,451,142 issued to Cetel et al.; US Patent No.
24 4,921,405, issued to Wilson; US Patent No. 4,145,481 issued to Gupta et al.; and US
25 Patent No. 5,732,467 issued to White et al.

26

1 Cetel discloses a turbine engine blade having a blade root with a surface having a thin
2 zone of fine grains. A plasma spray technique is used to form a thin layer of material
3 on the root or fir tree portion of the blade. The blade is then HIPed. After the HIP
4 process, the blade is solution heat treated and then machined. This reference is
5 directed to a process for modifying the root section of a turbine blade to improve the
6 mechanical properties of this area of the part. The root section is serrated and is
7 attached to the disc by inserting the root serrations into matching serrations of the
8 disc. The blade is normally produced, as relating to chemistry and microstructure, to
9 maximize the creep rupture and high cycle fatigue properties of the airfoil which is
10 exposed to the hot gas path. The root section of the part thus has those same
11 properties as the airfoil section. However, the root section of the blade is exposed to
12 stress of a type different than the airfoil section, usually referred to as low cycle
13 fatigue. The root section experiences colder operating temperatures than the airfoil
14 section and is not directly in the path of the hot gasses that flow through the engine.
15 Also, the root section is subjected to metal to metal stress during rotation resulting in
16 low cycle fatigue cracking. Cetel is concerned with treating only the fir tree or root
17 portion of the blade to improve its mechanical properties. The root portion or a new
18 or refurbished blade is treated with a plasma spray process, HIPing, and a heat
19 treatment and then machined. The blade is machined to remove material from a high
20 stress portion of the blade root. The material removed by the machining operation is
21 replaced by a zone of fine grains by a plasma spray technique. The part is processed
22 through a HIP cycle to densify the deposit, and then a heat treatment cycle to enhance
23 its properties. Finally, the root is machined back to the desired blueprint dimensions
24 and the part returned to service.

25

26 Wilson discloses a turbine engine blade having a single crystal body having an airfoil
27 section and an attachment or root section. A layer of polycrystalline superalloy is

1 applied to the attachment section, preferably by plasma spraying. The coated blade is
2 HIPed and then solution heat-treated to optimize the polycrystalline microstructure.

3

4 Gupta discloses a process for producing high temperature corrosion resistant metal
5 articles. A ductile metallic overlay is formed on the surface of an article substrate,
6 and an outer layer is applied over the overlay. The article is then subjected to a HIP
7 treatment to eliminate porosity and create an inter-diffusion between the outer layer
8 the overlay and the substrate.

9

10 None of these prior attempts provide for the effective and efficient restoration of the
11 critical airfoil dimensions of a gas turbine engine airfoil part. Typically, an airfoil
12 part will have to be discarded after it has gone through a certain number of repair
13 cycles. The stripping of the protective coating on the part during the repair process is
14 a major contributing factor resulting in the discarding of the part. After a number of
15 repair cycles the part simply does not have the minimum dimensional characteristics
16 necessary for it to perform its intended function. Therefore, there is a need for a
17 method for repairing gas turbine engine airfoil parts that effectively and efficiently
18 restores the critical airfoil dimensions of the part.

19

20 Turbine engine airfoil parts, such as vanes, are manufactured to precise tolerances that
21 determine the airflow characteristics for the part. The class of a turbine vane is the
22 angular relationship between the airfoil section and the inner and outer buttresses of
23 the vane. This angular relationship has a direct bearing on the angle of attack of the
24 airfoil section during the operation of the gas turbine engine. Over time, the angular
25 relationship between the airfoil section and the inner and outer buttresses of the vane
26 may become altered due to, for example, deformation of the airfoil section from
27 engine operation and repair processes and the like. Or, the particular angular

1 relationship of the airfoil section and the inner and outer buttresses as originally
2 manufactured may need to be changed to improve engine performance. In any event,
3 there is a need for a method of restoring or reclassifying a gas turbine engine airfoil
4 part.

5

6 SUMMARY OF THE INVENTION

7 The present invention overcome the drawbacks of the conventional art for repairing
8 gas turbine engine airfoil parts. It is an object of the present invention to provide a
9 method by which a deformed gas turbine engine airfoil part can be returned to the
10 dimensions required to place the part back into useful service. It is another object of
11 the present invention to obtain a diffusion bond between the coating material and the
12 substrate of a repaired gas turbine engine airfoil part. This diffusion bond is
13 extremely robust and results in a repaired engine part that has the appropriate
14 mechanical properties that allow the part to be safely returned to service. It is further
15 an object of the present invention to provide a method of repairing a turbine engine
16 airfoil part that offers substantial savings because it provides for the efficient and
17 effective repairing of expensive engine parts which otherwise might have been
18 discarded.

19

20 The present invention also overcomes the drawbacks of the conventional art and
21 provides a method of forming, treating and/or repairing metal components so that the
22 resulting metal component has improved metallurgical characteristics. It is an object
23 of the present invention to provide a method of forming a metal product having
24 diffusion bonding occurring between a metal substrate and an applied coating. It is
25 another object of the present invention to provide a method of forming cutting tools
26 having a wear resistant coating diffusion bonded to a cutting surface of a tool
27 substrate. It is still another object of the present invention to provide a method of

1 forming a cast metal product having a diffusion bonded coating formed on a cast
2 metal component.

3
4 The present invention also overcomes the drawbacks of the conventional art and
5 provides a method of reclassification of a gas turbine engine airfoil part. It is an
6 object of the present invention to provide a method for reclassification of the airfoil
7 part wherein the strength, integrity and other mechanical characteristics of the part are
8 not compromised by the reclassification procedure.

9
10 In accordance with the present invention, the dimensional differences between pre-
11 repaired dimensions of a turbine engine airfoil part and desired post-repair dimensions
12 of the turbine engine airfoil part are determined. A build-up thickness of coating
13 material required to obtain the desired post-repair dimensions of the turbine engine
14 airfoil part is determined. A high-density coating process, such as HVOF, is used to
15 coat the turbine engine airfoil part with a coating material to the determined build-up
16 thickness of coating material effective to obtain the desired post-repair dimensions
17 after performing a sintering heat treatment and a hot isostatic pressing treatment and,
18 if performed, after a re-application of a protective coating. The coating material
19 comprises a metal alloy capable of forming a diffusion bond with the substrate of the
20 turbine engine airfoil part. After the coating material is applied, the sintering heat
21 treatment process is performed to prevent gas entrapment of the coating material
22 and/or the diffusion bonding area during the hot isostatic pressing process. Then, the
23 hot isostatic pressing process is performed to obtain a post-repair turbine engine
24 airfoil part having the desired post-repair dimensions and having diffusion bonding
25 between the coating material and the turbine engine airfoil substrate.

1 A protective coating may be first removed from the turbine engine airfoil part prior to
2 performing the high-density coating process. Typically, this protective coating is
3 present on an airfoil part to protect it from the hot corrosive environment it
4 experiences during the operation of the gas turbine engine. After performing the hot
5 isostatic pressing process, the protective coating may be re-applied. In this case, the
6 build-up thickness may be determined to take into consideration the additional
7 thickness of the post-repaired part due to the addition of the protective coating and/or
8 a wear coating.

9
10 In the typical application of the inventive method, the metal alloy substrate of the
11 turbine engine airfoil part will comprise a nickel or cobalt-base superalloy. The step
12 of performing the high-density coating process may thus include performing a high-
13 density coating process such as a hyper velocity oxy-fuel thermal spray process or a
14 detonation gun process to apply a high-density coating having the same nickel or
15 cobalt-base superalloy composition as the metal alloy substrate.

16
17 The sintering heat treatment comprises sintering at a temperature at or about 2150
18 degrees F for about 2 hours, which has been found to effectively prevent gas
19 entrapment of the applied high-density coating during the hot isostatic pressing
20 process. In the case of a nickel or cobalt-base superalloy substrate, the hot isostatic
21 pressing treatment can be performed at a temperature of about 2200F in about 15 KSI
22 argon for about 4 hours. The parameters of the hot isostatic pressing treatment
23 typically call for heating the engine part to a temperature that is substantially 80% of
24 the melting point of the metal alloy; and pressurizing the engine part to a pressure
25 substantially between 20 and 50 percent of the yield strength of the metal alloy in an
26 inert gas atmosphere.

1 The dimensional differences between the pre-repaired dimensions of the turbine
2 engine airfoil part and the desired post-repair dimensions of the turbine engine airfoil
3 part are measured from at least one of the chordal and length dimensions of the airfoil
4 part. By performing the inventive method for repairing a gas turbine engine airfoil
5 part, the post-repair dimensions are equal to the dimensions necessary for effectively
6 returning the part to active service. The diffusion bonding between the coating
7 material and the substrate ensures that the repaired airfoil part is robust enough to
8 withstand the highly demanding environmental conditions present in an operating gas
9 turbine engine.

10
11 In accordance with another embodiment of the inventive method, a turbine engine
12 part, which is comprised of a metal or metal alloy, is first cleaned. If necessary,
13 eroded portions of the turbine engine part are welded using a weld material comprised
14 of the same metal or metal alloy as the parent or original metal engine part. The
15 welding operation is performed to build up heavily damaged or eroded portions of the
16 turbine engine part. If the part is not heavily damaged, the welding operation may be
17 obviated. The welding operation will typically produce weld witness lines. The weld
18 witness lines are ground flush to prevent blast material from becoming entrapped in
19 the weld witness lines. Portions of the engine part that are not to be HVOF sprayed
20 are masked, and the engine part is again cleaned in preparation for HVOF spraying.
21 HVOF plasma spraying of the unmasked portions of the engine part is performed.
22 The HVOF plasma spray material (coating material) is comprised of the same metal
23 alloy as the parent or original metal engine part. The HVOF plasma spray material is
24 applied so as to build up a chordal dimension of the engine part to a thickness greater
25 than the thickness of an original chordal dimension of the engine part. After the
26 HVOF spray material is applied, a sintering heat treatment process is performed to
27 prevent gas entrapment of the coating material and/or the diffusion bonding area

1 during the hot isostatic pressing process. A hot isostatic pressing (HIP) treatment is
2 performed on the coated engine part to densify the coating material, to create a
3 diffusion bond between the coating material and the parent and the weld material,
4 and to eliminate voids between the turbine engine part, the weld material and the
5 coated material. Finally, the engine part is machined, ground and/or polished to the
6 original or desired dimensions.

7

8 The present invention offers a substantial improvement over the prior attempts at
9 repairing turbine engine airfoil parts. By the inventive method, the resulting repaired
10 part is returned to the dimensions required to place the part back into useful service.
11 Further, in accordance with the present invention, a diffusion bond is obtained
12 between the coating material and the substrate of the turbine engine airfoil part. This
13 diffusion bond is extremely robust and results in a repaired engine part that has the
14 appropriate mechanical properties that allow the part to be safely returned to service.
15 Thus, the inventive method of repairing a turbine engine airfoil part offers substantial
16 savings because it provides for the efficient and effective repairing of expensive
17 engine parts which otherwise might have been discarded.

18

19 In accordance with another aspect of the present invention, a method of forming a
20 metal product having diffusion bonding occurring between a metal substrate and an
21 applied coating is provided. The first step of the inventive method is to determine the
22 attributes of a final workpiece product. For example, if the final workpiece product is
23 a cutting tool the attributes include a wear resistant surface formed on a relatively
24 inexpensive tool substrate. An appropriate substrate composition is then determined
25 depending on the selected attributes. In the example of a cutting tool, the substrate
26 composition may be high speed steel, which is relatively inexpensive to form but
27 durable enough for its intended purpose. A workpiece substrate is formed to near-

1 finished dimensions, using known processes such as casting, extruding, molding,
2 machining, etc. An appropriate coating material composition is determined
3 depending on the selected attributes. Again, in the example of a cutting tool, the
4 coating material could be selected from a number of relatively hard and durable
5 metals and alloys such as Cobalt, Carbide, TiN, etc. The selection of both the
6 substrate and coating composition also depends on their metallurgical compatibility
7 with each other.

8
9 The workpiece substrate is prepared for a high-density coating process. The
10 preparation may include cleaning, blasting, machining, masking or other like
11 operations. Once the workpiece substrate has been prepared, a high-density coating
12 process is performed to coat the workpiece substrate. The coating material is built-up
13 to a thickness that is effective to obtain desired finished dimensions after performing a
14 hot isostatic pressing treatment (described below). The high-density coating process
15 may comprise performing a hyper velocity oxy-fuel thermal spray process. In the
16 case of HVOF, a fuel gas and oxygen are used to create a combustion flame at 2500
17 to 3100°C. The combustion takes place at a very high chamber pressure and a
18 supersonic gas stream forces the coating material through a small-diameter barrel at
19 very high particle velocities. The HVOF process results in extremely dense, well-
20 bonded coatings. Typically, HVOF coatings can be formed nearly 100% dense, with
21 at a porosity of about 0.5%. The high particle velocities obtained using the HVOF
22 process results in relatively better bonding between the coating material and the
23 substrate, as compared with other coating methods such as the conventional plasma
24 spray method or the chemical vapor deposition method. However, the HVOF process
25 forms a bond between the coating material and the substrate that occurs primarily
26 through mechanical adhesion at a bonding interface. As will be described below, in
27 accordance with the present invention this mechanical bond is converted to a

1 metallurgical bond by creating a diffusion bond between the coating material and the
2 workpiece substrate. This diffusion bond does not have the interface boundary which
3 is usually the site of failure.

4

5 The diffusion bond is created by subjecting the coated workpiece substrate (or, in the
6 case of the inventive repair method, the coated airfoil part) to a hot isostatic pressing
7 (HIP) treatment. The appropriate hot isostatic pressing treatment parameters are
8 selected depending on the coating, the workpiece substrate and the final attributes that
9 are desired. The hot isostatic pressing treatment is performed on the coated
10 workpiece substrate to obtain a metal product having the desired finished dimensions
11 and diffusion bonding between the coating material and the workpiece substrate.

12

13 HIP treatment is conventionally used in the densification of cast metal components
14 and as a diffusion bonding technique for consolidating powder metals. In the HIP
15 treatment process, a part to be treated is raised to a high temperature and isostatic
16 pressure. Typically, the part is heated to 0.6 - 0.8 times the melting point of the
17 material comprising the part, and subjected to pressures on the order of 0.2 to 0.5
18 times the yield strength of the material. Pressurization is achieved by pumping an
19 inert gas, such as Argon, into a pressure vessel. Within the pressure vessel is a high
20 temperature furnace, which heats the gas to the desired temperature. The temperature
21 and pressure is held for a set length of time, and then the gas is cooled and vented.

22

23 In accordance with the present invention, the HIP treatment process is performed on a
24 HVOF coated substrate to convert the adhesion bond, which is merely a mechanical
25 bond, to a diffusion bond, which is a metallurgical bond. In accordance with the
26 present invention, an HVOF coating process is used to apply the coating material
27 having sufficient density to effectively undergo the densification changes that occur

1 during the HIP process. After the HVOF spray material is applied, a sintering heat
2 treatment process can be performed to further densify the coating to prevent gas
3 entrapment of the coating material and/or the diffusion bonding area during the hot
4 isostatic pressing process. If the coating material and the workpiece substrate are
5 comprised of the same metal composition, then the diffusion bonding results in a
6 particularly seamless transition between the substrate and the coating.

7
8 The inventive method can be used for forming a metal product having a wear resistant
9 surface. This method can be employed to produce, for example, a long lasting cutting
10 tool from a relatively inexpensive cutting tool substrate. In accordance with this
11 aspect of the invention, a workpiece substrate is formed to near-finished dimensions.
12 A high-density coating process, such as a hyper velocity oxy-fuel thermal spray
13 process, is performed to coat the workpiece substrate with a wear resistant coating
14 material. The coating material is built-up to a thickness that is effective to obtain
15 desired finished dimensions after performing a hot isostatic pressing treatment. A
16 sintering heat treatment step may be performed improve the density of the coating
17 material and prevent gas entrapment during the hot isostatic pressing treatment. The
18 hot isostatic pressing treatment is performed on the coated workpiece substrate to
19 obtain a metal product having the desired finished dimensions and diffusion bonding
20 between the coating material and the workpiece substrate.

21
22 The inventive method can also be used for forming a cast metal product. This method
23 can be employed to produce, for example, a cast part having a hard and/or smooth
24 surface. In accordance with the present invention, a part is cast to dimensions to less
25 than the finished dimensions, or a cast part is machined to less than the finished
26 dimensions. The cast part is then coated using the HVOF coating method as
27 described herein. The HVOF coating is applied to a thickness sufficient to bring the

1 part to its finished dimensions. The HVOF coated, cast part is then HIP treated as
2 described herein to obtain a finished part having desired dimensions and surface
3 characteristics.

4

5 In accordance with this aspect of the invention, a cast metal workpiece is provided.
6 The cast metal workpiece may be formed from any conventional casting method such
7 as: investment, sand and resin shell casting.

8

9 The cast metal workpiece is machined, if necessary, to near-finished dimensions. A
10 high-density coating process, such as a hyper velocity oxy-fuel thermal spray process
11 (HVOF), is performed to coat the workpiece substrate with a coating material. The
12 coating material is built-up to a thickness effective to obtain desired finished
13 dimensions after performing a hot isostatic pressing treatment. A sintering heat
14 treatment step may be performed improve the density of the coating material and
15 prevent gas entrapment during the hot isostatic pressing treatment. The hot isostatic
16 pressing treatment is performed on the coated workpiece substrate to obtain a metal
17 product having the desired finished dimensions and diffusion bonding between the
18 coating material and the workpiece substrate.

19

20 In accordance with another aspect of the present invention, the reclassification of a
21 gas turbine engine airfoil part is obtained. The dimensional differences between pre-
22 reclassified dimensions of the buttresses of a turbine engine airfoil part and desired
23 post-reclassified dimensions of the buttresses are determined. That is, the change in
24 shape of the inner buttress and outer buttress necessary to obtained a desired angular
25 relationship between the airfoil section and the buttresses is determined. Build-up
26 thickness of coating material required to obtain the desired post-reclassified
27 dimensions of the buttresses is determined. A high-density coating process, such as

1 HVOF, is used to coat the buttresses of the turbine engine airfoil part with a coating
2 material. The portions of the part that are not to be built up, such as the airfoil section
3 and parts of the buttresses, may be masked before applying the high-density coating.
4 Also, some of the coated surfaces of the part may need to be built up more than
5 others. The coating material is applied to the determined build-up thickness of
6 coating material effective to obtain the desired post-reclassification dimensions after
7 performing a hot isostatic pressing treatment, and after the selective removal of some
8 of the original buttress material and some of the built up coating material. A sintering
9 heat treatment may be performed before the hot isostatic pressing treatment.

10

11 As discussed herein, the coating material comprises a metal alloy capable of forming
12 a diffusion bond with the substrate of the turbine engine airfoil part. After the
13 coating material is applied, the sintering heat treatment process may be performed to
14 prevent gas entrapment of the coating material and/or the diffusion bonding area
15 during the hot isostatic pressing process. Then, the hot isostatic pressing (HIP)
16 process is performed so that the buttresses of the turbine engine airfoil part have a
17 robust diffusion bonding between the coating material and the original material of the
18 buttresses. Having built up the appropriate dimensions of the inner buttress and outer
19 buttress, the reclassification of the part is obtained by selectively removing the
20 original buttress material and, if necessary, some of the built up material until the
21 angular relationship between the airfoil section and the inner and outer buttresses is
22 obtained. The material can be removed through milling, grinding, or other suitable
23 and well known machining operations. Further, to facilitate obtaining the correct
24 dimensions the centerline position of the airfoil part can be located and held by
25 mounting the part in a suitable holding fixture when machining the buttresses.

26

1 The fixture may be so constructed so that a vane that has at least a minimum amount
2 of material built up on its buttresses can be machined and reclassified. In this case, it
3 may not be necessary to determine the dimensional differences or the required build-
4 up thickness. Rather, the inventive high density coating and HIPing process (and, if
5 needed sintering) can be performed to build up at least the minimum amount of
6 material diffusion bonded to the buttresses. Then, the vane is placed in the fixture and
7 the excess material (both original buttress material and the built-up material) is
8 machined until the buttresses have been reshaped and the vane reclassified as
9 intended.

11 BRIEF DESCRIPTION OF THE DRAWINGS

12 Figure 1(a) is a flow chart showing the steps of the inventive method for repairing a
13 gas turbine engine airfoil part;

15 Figure 1(b) is a flow chart showing the steps of the inventive method of forming
16 metal products and metal components having a wear resistant coating;

18 Figure 2(a) is a schematic view of a tool substrate provided in accordance with the
19 inventive method of forming metal components having a wear resistant coating;

21 Figure 2(b) is a schematic view of the tool substrate having a wear resistant coating
22 applied using an HVOF thermal spray process in accordance with the inventive
23 method of treating metal components having a wear resistant coating;

25 Figure 2(c) is a schematic view of the HVOF spray coated tool substrate undergoing a
26 HIP treatment process in a HIP vessel in accordance with the inventive method of
27 forming metal components having a wear resistant coating;

1

2 Figure 2(d) is a schematic view of the final HVOF spray coated and HIP treated tool
3 having a wear resistant coating layer diffusion bonded to the tool substrate in
4 accordance with the inventive method of forming metal components having a wear
5 resistant coating;

6

7 Figure 3(a) is a schematic perspective view of a cast metal component undergoing a
8 machining operation in accordance with the inventive method of forming a metal
9 product;

10

11 Figure 3(b) is a schematic perspective view of the machined cast metal component in
12 accordance with the inventive method of forming a metal product;

13

14 Figure 3(c) is a schematic perspective view of the machined cast metal component
15 having a coating applied using an HVOF thermal spray process in accordance with
16 the inventive method of forming a metal product;

17

18 Figure 3(d) is a schematic perspective view of the HVOF spray coated machined cast
19 metal component undergoing a HIP treatment process in a HIP vessel in accordance
20 with the inventive method of forming a metal product;

21

22 Figure 3(e) is a schematic perspective view of the final HVOF spray coated and HIP
23 treated machined cast metal product having a coating layer diffusion bonded to the
24 machined cast metal component in accordance with the inventive method of forming
25 a metal product;

26

1 Figure 4 is a flow chart showing the steps of the inventive method of repairing a
2 turbine engine part;

3

4 Figure 5(a) is a schematic side view of a worn turbine engine part before undergoing
5 the inventive method of repairing a turbine engine part;

6

7 Figure 5(b) is a schematic cross-sectional view of the worn turbine engine part before
8 undergoing the inventive method of repairing a turbine engine part;

9

10 Figure 6(a) is a schematic side view of the worn turbine engine part showing the worn
11 areas to be repaired using the inventive method of repairing a turbine engine part;

12

13 Figure 6(b) is a schematic cross-sectional view of the worn turbine engine part
14 showing the worn areas to be repaired using the inventive method of repairing a
15 turbine engine part;

16

17 Figure 7(a) is a schematic side view of the worn turbine engine part showing the worn
18 areas filled in with similar weld material in accordance with the inventive method of
19 repairing a turbine engine part;

20

21 Figure 7(b) is a schematic cross-sectional view of the worn turbine engine part
22 showing the worn areas filled in with similar weld material in accordance with the
23 inventive method of repairing a turbine engine part;

24

25 Figure 8(a) is a schematic side view of the welded turbine engine part showing areas
26 to be built up with similar coating material using an HVOF spray coating process in
27 accordance with the inventive method of repairing a turbine engine part;

1

2 Figure 8(b) is a schematic cross-sectional view of the welded turbine engine part
3 showing areas to be built up with similar coating material using an HVOF spray
4 coating process in accordance with the inventive method of repairing a turbine engine
5 part;

6

7 Figure 9(a) is a schematic side view of the HVOF built up, welded turbine engine part
8 showing an area masked before performing the HVOF spray coating process in
9 accordance with the inventive method of repairing a turbine engine part;

10

11 Figure 9(b) is a schematic cross-sectional view of the HVOF built up, welded turbine
12 engine part in accordance with the inventive method of repairing a turbine engine
13 part;

14

15 Figure 10 is a schematic view of the HVOF built up, welded turbine engine part
16 undergoing a HIP treatment process in a HIP vessel in accordance with the inventive
17 method of repairing a turbine engine part;

18

19 Figure 11(a) is a schematic side view of the final HVOF spray coated and HIP
20 repaired turbine engine part having a similar metal coating layer diffusion bonded to
21 the original parent substrate and welded portions in accordance with the inventive
22 method of repairing a turbine engine part;

23

24 Figure 11(b) is a schematic cross-sectional view of the final HVOF spray coated and
25 HIP repaired turbine engine part having a similar metal coating layer diffusion
26 bonded to the original parent substrate and welded portions in accordance with the
27 inventive method of repairing a turbine engine part;

1

2 Figure 12(a) is a side view of a prior art tool bit coated with a wear resistant coating;

3

4 Figure 12(b) is a side view of a prior art tool bit having a fixed wear resistant cutting
5 tip;

6

7 Figure 13 is a flow chart showing the steps of the inventive method for reclassifying a
8 gas turbine engine airfoil part;

9

10 Figure 14(a) is a front view of a vane from a gas turbine engine showing the airfoil
11 section, the outer buttress and the inner buttress;

12

13 Figure 14(b) is a partial top view of the vane shown in Figure 14(a) showing the outer
14 buttress and angle α indicating the angular relationship between the airfoil and the
15 outer buttress;

16

17 Figure 14(c) is a partial bottom view of the vane shown in Figure 14(a) showing the
18 inner buttress and angle α' indicating the angular relationship between the airfoil and
19 the inner buttress;

20

21 Figure 14(d) is a partial left-side view of the vane shown in Figure 14(a) showing the
22 leading edge foot of the inner buttress and the outer foot front face of a buttress rail of
23 the outer buttress; and

24

25 Figure 14(e) is a partial right-side view of the vane shown in Figure 14(a) showing the
26 trailing edge foot of the inner diameter buttress and the other buttress rail of the outer
27 diameter buttress.

1

2 **DETAILED DESCRIPTION OF THE INVENTION**

3 For purposes of promoting an understanding of the principles of the invention,
4 reference will now be made to the embodiments illustrated in the drawings and
5 specific language will be used to describe the same. It will nevertheless be
6 understood that no limitation of the scope of the invention is thereby intended, there
7 being contemplated such alterations and modifications of the illustrated device, and
8 such further applications of the principles of the invention as disclosed herein, as
9 would normally occur to one skilled in the art to which the invention pertains.

10

11 Referring to Figure 1(a), in accordance with the present invention, the dimensional
12 differences between pre-repaired dimensions of a turbine engine airfoil part and
13 desired post-repair dimensions of the turbine engine airfoil part are determined (Step
14 One-B). The turbine engine airfoil part has a substrate comprised of a superalloy. A
15 build-up thickness of coating material required to obtain the desired post-repair
16 dimensions of the turbine engine airfoil part is determined (Step Two). A high-
17 density coating process, such as HVOF, is used to coat the turbine engine airfoil part
18 with a coating material to the determined build-up thickness of coating material
19 effective to obtain the desired post-repair dimensions after performing a sintering heat
20 treatment and a hot isostatic pressing treatment (Step Three). The coating material
21 comprises a metal alloy capable of forming a diffusion bond with the substrate of the
22 turbine engine airfoil part. After the coating material is applied, a sintering heat
23 treatment process is performed to prevent gas entrapment of the coating material
24 and/or the diffusion bonding area during the hot isostatic pressing process (Step
25 Four). Then, the hot isostatic pressing process is performed to obtain a post-repair
26 turbine engine airfoil part having the desired post-repair dimensions and having

1 diffusion bonding between the coating material and the turbine engine airfoil substrate
2 (Step Five).

3

4 In accordance with the present invention, a protective coating must be first removed
5 from the turbine engine airfoil part prior to performing the high-density coating
6 process (Step One-A). After performing the hot isostatic pressing process, a
7 protective coating may be re-applied (Step Six). In this case, the build-up thickness
8 may determined in Step Two to take into consideration the additional thickness of the
9 post-repaired part due to the addition of the protective coating.

10

11 Typically, this protective coating is present on an airfoil part to protect it from the hot
12 corrosive environment it experiences during service. This protective coating must be
13 removed during the inspection and/or repair process. After undergoing a number of
14 inspection and/or repair cycles, the airfoil part was conventionally discarded simply
15 because the airfoil dimensions of the part were too deformed for the part to be usable.
16 However, in accordance with the present inventive repair method, the airfoil
17 dimensions are restored and a robust repaired airfoil part is obtained

18

19 In the typical application of the inventive method, the metal alloy substrate of the
20 turbine engine airfoil part will comprise a nickel or cobalt-base superalloy. The step
21 of performing the high-density coating process (Step Three) may thus include
22 performing a high-density coating process such as a hyper velocity oxy-fuel thermal
23 spray process or a detonation gun process to apply a high-density coating having the
24 same nickel or cobalt-base superalloy composition as the metal alloy substrate.

25

26 In an embodiment of the invention in which the coating material and the substrate
27 alloy comprise INCO713C nickel or cobalt-base superalloy, the sintering heat

1 treatment (Step Four) comprises sintering at a temperature at or about 2150 degrees F
2 for about 2 hours, which has been found to effectively prevent gas entrapment of the
3 applied high-density coating during the hot isostatic pressing process. In the case of
4 the nickel or cobalt-base superalloy substrate, an effective hot isostatic pressing
5 treatment (Step Five) can be performed at a temperature of about 2200F in about 15
6 KSI argon for about 4 hours. The parameters of the hot isostatic pressing treatment
7 typically call for heating the engine part to a temperature that is substantially 80% of
8 the melting point of the metal alloy; and pressurizing the engine part to a pressure
9 substantially between 20 and 50 percent of the yield strength of the metal alloy in an
10 inert gas atmosphere.

11
12 The dimensional differences between the pre-repaired dimensions of the turbine
13 engine airfoil part and the desired post-repair dimensions of the turbine engine airfoil
14 part are measured from at least one of the chordal and length dimensions of the airfoil
15 part (Step One-B). By performing the inventive method for repairing a gas turbine
16 engine airfoil part, the post-repair dimensions are equal to the dimensions necessary
17 for effectively returning the part to active service. The obtained diffusion bonding
18 between the coating material and the substrate ensures that the repaired airfoil part is
19 robust enough to withstand the highly demanding environmental conditions present in
20 an operating gas turbine engine. Thus, the present invention offers substantial cost
21 savings over having to replace a turbine gas engine airfoil part which otherwise might
22 have been discarded.

23
24 The present invention can be used as a process for restoring critical gas path area
25 dimensions in cast nickel or cobalt-base superalloy vane components. These
26 dimensions may become altered due to erosion or particle strikes during the service

1 life of the part, and/or may become altered during an inspection or repair process
2 wherein a protective coating is stripped from the part.

3

4 The inventive process, referred to herein as "recast", briefly consists of applying a
5 pre-alloyed metal powder, compositionally identical to the superalloy used in the
6 original manufacture of the vane being repaired, directly on dimensionally discrepant
7 surfaces, densifying the metal powder coating, and causing it to bond to the affected
8 surface.

9

10 More specifically, in the preferred embodiment of the invention candidate recast
11 surfaces are abrasively clean, thermal sprayed using high velocity oxy fuel processes
12 (HVOF), sintered, and hot isostatically pressed (HIPed).

13

14 Thermal spray metal powders, produced by a vacuum/inert gas atomization processes,
15 are applied directly to the dimensionally discrepant surfaces of a turbine engine airfoil
16 part using robotic HVOF processes carefully controlled to produce dense coatings
17 while minimizing thermal gradients and oxidative solute losses.

18

19 Properly applied HVOF coatings are dense but sometimes contain interconnected
20 micropores. In accordance with the present invention, such "porous" HVOF coatings
21 are more fully densified by sintering and subsequently diffusion-bonded to substrate
22 surfaces by HIPing at temperatures and pressures commensurate with the nickel or
23 cobalt-base alloy under consideration.

24

25 Recast surfaces are compositionally identical to, but microstructurally different from,
26 original or "as-cast" substrates. As-cast substrates are defined herein as a substrate
27 formed by a conventional casting process, such as the lost wax or investment casting

process described above. The microstructures of cast nickel or cobalt-base superalloy substrate materials such as used in the manufacture of gas turbine vanes generally consist of relatively large amount of an intermetallic precipitate referred to as "gamma prime" within, and networks of carbides and borides within and around, large "gamma" matrix grains. The amount and morphology of gamma prime, carbides, and borides are determined by composition, processing history, and heat treatment.

Recast microstructures similarly consist of gamma prime, carbides, and borides precipitated in and around gamma matrix grains; but, recast matrix grains are considerably smaller than as-cast grains. Recast gamma prime, carbide and boride precipitates are similarly finer than as-cast. In addition, some of the more reactive solutes (e.g., aluminum) in the thermal spray powders oxidize during the HVOF spray process to form oxide particles which become randomly dispersed in the recast deposit.

Articles repaired by recast are best described as bi-metallic composites comprised of recast coatings bonded to as-cast substrates. The mechanical properties of such repaired articles vary depending on the relative volume fraction of the recast coating, the specific alloy(s) under consideration, and processing history.

Example of Recast INCO713C/cast INCO713C Composite Mechanical

Properties Obtained in Accordance with the Present Invention:

Representative tensile and stress-rupture properties of recast INCO713C/cast INCO713C composite test specimens were measured to more fully elucidate the recast process.

INCO713C was selected as the base nickel or cobalt-base superalloy for measurement because it is specified by a large number of engine manufactures for gas turbine component applications, and is bill-of-material for JT8D second-stage vanes, a candidate component for the inventive recast repair method.

Near cast-to-size INCO713C test bars were machined into ASTM proportioned mechanical test specimens with tapered (approximately three percent) gauge lengths. The average minimum gauge length diameter was 0.2137 inches.

The machined test specimens were grit-blasted with silicon carbide, ultrasonically cleaned, and robotically sprayed with INCO713C powder using Diamond Jet HVOF processes. The composition of the INCO713C powder used in these evaluations is shown in Table I.

Table I: Certified Compositions of INCO713C Atomized Powder and Cast-To-Size Test Bars

<u>Element</u>	<u>EMS 55079</u>	<u>Atomized Powder</u>	<u>Cast-To-</u>
<u>Size</u>			
Test Bars			
(Heat # 8616)			
Nickel	Balance	Balance	Balance
Chromium	11.0 to 13.0	13.6	13.67
Aluminum	5.5 to 6.5	5.86	5.61
Molybdenum	3.8 to 5.2	4.39	4.06
Columbium	1.5 to 2.5	2.1	2.08

1	Titanium	0.4 to 1.0	0.9	0.84
2	Zirconium	0.05 to 0.15	0.07	0.05
3	Carbon	0.05 to 0.07	0.1	0.13
4	Boron	0.005 to 0.015	0.01	0.008
5				
6	Cobalt	1.00 max.	<0.01	<0.05
7	Silicon	0.50 max.	0.09	<0.05
8	Copper	0.05 max.	0.04	<0.05
9	Iron	0.25 max.	0.18	<0.05
10	Manganese	0.25 max.	0.01	<0.05
11	Sulfur	0.015 max.	0.002	<0.05
12	Phosphorus	0.015 max.		

13

14 Sufficient HVOF coating was applied to increase the composite specimen gauge
 15 length diameter to approximately 0.250 inches. The sprayed test bars were then
 16 sintered at 2150F for 2 hours in vacuum, HIPed at 2200F in 15 KSI argon for 4 hours
 17 in a standard commercial HIP toll cycle, and tested for room temperature tensile and
 18 elevated-temperature stress-rupture.

19

20 The composite test specimens used for these measurements were nominally
 21 comprised of 28 percent recast INCO713C and 72 percent as-cast INCO713C. The
 22 recast INCO713C percentage varied, however, from 25.5 to 30.9 percent depending
 23 on precise machined and sprayed specimen dimensions.

24

25 Mechanical Properties:

26 The room temperature tensile and 1800F stress-rupture properties of the as-cast

27 INCO713C core material used in these measurements are summarized in Table II.

Table II: INCO713C Heat # 8616 Qualification Tests

1. Room Temperature Tensile

a.	0.2% Y.S.	108 KSI		
	UTS	126 KSI		
	Elongation	6.0%		
b.	0.2% Y.S.	112.2 KSI	111.0 KSI	
	UTS	126 KSI	135.7 KSI	
	Elongation	6.3%	6.7%	

2. Stress-Rupture

a.	Temperature	Stress	Rupture Life	Elongation
	1800F	22 KSI	30.0 hours	
	1800F	24 KSI	14.8 hours	14.0%
b.	1800F	22 KSI	55.3 hours	9.1%
	1800F	22 KSI	58.2 hours	10.3%

The room-temperature tensile and 1800F stress-rupture properties of the 28 percent recast INCO713C composite test specimens are summarized in Table III.

Table III: Measured Tensile and Stress-Rupture Properties of Composite Cast/Recast
INCO713C Test Specimens

1. Room Temperature Tensile Properties

<u>Specimen</u>	<u>0.2 YS</u>	<u>UTS</u>	<u>Elongation</u>
#1	123.3 KSI	150.3 KSI	5.6%
#2	122.0 KSI	151.5 KSI	6.6%
#3	122.4 KSI	148.1 KSI	6.7%
Average	122.4 KSI	150.0 KSI	6.3%

2. Stress-Rupture Properties

<u>Specimen</u>	<u>Rupture Life</u>	<u>Elongation</u>	<u>Reduction in Area</u>
@ 1800F/22 KSI			
(stress calculated on cast INCO713C cross-section only)			

#4	60.9 hrs.	10.7%	21.1%
#5	55.9 hrs.	6.3%	17.8%
#6	60.9 hrs.	7.1%	16.8%

@ 1600F/42 KSI

(stress calculated on cast INCO713C cross-section only)

#5	202.5 hrs.	6.9%	12.2%
----	------------	------	-------

1 #6 >212.5 hrs. 4.9% 8.6%

2

3 The room temperature yield and ultimate tensile strengths of the 28 percent recast
4 INCO713C composite test specimens were approximately 11 percent higher than
5 those of as-cast INCO713C core material. The room temperature ductility of the 28
6 percent recast INCO713C composite test specimens was virtually identical to that of
7 the as-cast INCO713C core material.

8

9 The as-cast INCO713C core material and the 28 percent recast INCO713C composite
10 test specimens were tested for stress-rupture at 1800F under "constant load"
11 conditions to experimentally assess the effect of the recast process on the sustained,
12 high-temperature, load-bearing capacity of as-cast INCO713C.

13

14 The approximate time to rupture as-cast INCO713C at 1800F/22 KSI, as estimated
15 from available "Larsen-Miller" correlations, is 48 hours. The time to rupture the as-
16 cast INCO713C core material test bars at 1800F/22 KSI was 30.0 hours. The average
17 time to rupture machined as-cast INCO713C test specimens at 1800F/22 KSI was
18 56.5 hours. The average as-cast INCO713C 1800F/22 KSI stress-rupture life was 45
19 hours, plus or minus 15 hours.

20

21 The 28 percent recast INCO713C composite test specimens were tested at 1800F
22 under loads sufficient to produce 22 KSI stress based on as-cast INCO713C substrate
23 dimensions rather than composite test specimen dimensions. Test loads ranged from
24 795 to 799 pounds (797 pounds average) depending on precise as-cast INCO713C
25 machined diameters. Corresponding composite specimen stresses ranged from 15 to
26 16 KSI.

27

1 The average time to rupture the 28 percent INCO713C composite test specimens
2 under such "constant load" test conditions was 60.9 hours at 1800F.

3
4 **Data Analyses:**

5 The data summarized in Table III show that the recast process augments the room
6 temperature tensile properties of as-cast INCO713C:

7
8 Assuming the room temperature tensile properties of the as-cast INCO713C substrate
9 remain unchanged by the thermal treatments associated with the recast process, "rule
10 of mixture" analyses of the room temperature 28 percent recast INCO713C composite
11 tensile data summarized in Table III indicate that the recast INCO713C portion of the
12 composite has the following room temperature tensile properties:

13
14 150 KSI 0.2% yield strength
15 190 KSI ultimate tensile strength
16 5.8% elongation

17
18 The data summarized in Table III similarly show that the recast process augments the
19 sustained high-temperature, load-bearing capacity of as-cast INCO713C.

20
21 "Load partitioning analysis", for lack of a better description, were used to distinguish
22 the stress-rupture strength properties of the recast INCO713C coating from those of
23 the as-cast INCO713C substrate.

24
25 "Larsen-Miller" stress-rupture data correlation's suggest that the stress required to
26 increase the 1800F rupture life of an as-cast INCO713C substrate specimen to 60.9
27 hours is only 21 KSI. The load required to develop a stress of 21 KSI, based on an

1 average 0.2145 inch as-cast INCO713C substrate diameter, is 759 pounds. Since 797
2 pounds were applied to the 28 percent recast INCO713C composite specimens tested
3 at 1800F/16 KSI, it follows that the balance of the load (39 pounds) was
4 accommodated by the recast INCO713C coating.

5
6 Since the cross-sectional area of the recast INCO713C coating in the 28 percent recast
7 INCO713C composite specimens was 0.0161 square inches, the recast INCO713C
8 coating stress was 2.4 KSI. The 1800F/60.9 hour stress-rupture strength of recast
9 INCO713C is, therefore, approximately 2.4 KSI.

10
11 Two 28 percent recast INCO713C composite test specimens were similarly tested in
12 stress-rupture at 1600F under loads calculated to develop a stress of 42 KSI based on
13 as-cast INCO713C substrate dimensions.

14
15 One of the 28 percent recast INCO713C composite test specimens ruptured in 202.5
16 hours at 1600F/42 KSI (based on as-cast substrate dimensions) while the other was
17 arbitrarily terminated without rupture after 212.5 hours. An as-cast INCO713C test
18 specimen might be expected to rupture in approximately 100 hours at 1600F/42 KSI.

19
20 "Load-partitioning analyses" of these 1600F stress-rupture test results suggest that the
21 1600F/200 hour stress-rupture strength of the recast INCO713C coating is greater
22 than 8 KSI.

23
24 The stress-rupture properties of the recast INCO713C coating, as inferred from "load
25 partitioning analyses", generally correspond to those of wrought nickel or cobalt-base
26 levels through post HIP heat treatments.

1 The experimental data discussed above indicate that recast INCO713C coating:

2 1. have intrinsically higher room temperature tensile strength than as-cast

3 INCO713C; and,

4 2. have intrinsic stress-rupture strengths approximately equivalent to wrought nickel
5 or cobalt-base alloys.

6

7 More importantly, the experimental data presented and discussed in this study
8 convincingly demonstrate that the recast process augments the room-temperature
9 tensile and sustained high-temperature, load-bearing capacities of as-cast INCO713C.

10

11 In accordance with another aspect of the present invention, a method of forming metal
12 products and components having a durable wear resistant coating is provided. Figure
13 1(b) is a flow chart showing the steps of the inventive method of forming metal
14 products and metal components having a wear resistant coating. This method obtains
15 a metal product having robust diffusion bonding occurring between a metal substrate
16 and an applied coating. The first step of the inventive method is to determine the
17 attributes of a final workpiece product (Step One). For example, if the final
18 workpiece product is a cutting tool the attributes include a wear resistant surface
19 formed on a relatively inexpensive tool substrate 10. If the final workpiece is a cast
20 metal component, a decorative, smooth final surface may be desired on a cast
21 substrate 16.

22

23 An appropriate substrate composition is then determined (Step Two) depending on the
24 selected attributes. In the example of a cutting tool, the substrate composition may be
25 high speed steel, which is relatively inexpensive to form but durable enough for its
26 intended purpose. In the case of a cast metal component, the cast workpiece substrate
27 can be formed from cast iron or aluminum (or other cast metal or metal alloy). A

1 workpiece substrate is formed to near-finished dimensions (Step Three), using known
2 processes such as casting, extruding, molding, machining, etc. An appropriate
3 coating material 12 composition is determined depending on the selected attributes
4 (Step Four). Again, in the example of a cutting tool the coating material 12 could be
5 selected from a number of relatively hard and durable metals and alloys such as
6 Cobalt, Carbide, TiN, etc. In the example of the cast metal component, aluminum
7 oxide may be chosen to provide both a decorative and corrosion resistant surface.
8 The selection of both the substrate and coating composition also depends on their
9 metallurgical compatibility with each other.

10

11 The workpiece substrate is prepared for a high-density coating process (Step Five).
12 The preparation may include cleaning, blasting, machining, masking or other like
13 operations. Once the workpiece substrate has been prepared, a high-density coating
14 process is performed to coat the workpiece substrate (Step Six). The coating material
15 12 is built-up to a thickness that is effective to obtain desired finished dimensions
16 after performing a hot isostatic pressing treatment (described below). The high-
17 density coating process may comprise performing a hyper velocity oxy-fuel thermal
18 spray process. In the case of HVOF, a fuel gas and oxygen are used to create a
19 combustion flame at 2500 to 3100°C. The combustion takes place at a very high
20 chamber pressure and a supersonic gas stream forces the coating material 12 through
21 a small-diameter barrel at very high particle velocities. The HVOF process results in
22 extremely dense, well-bonded coatings. Typically, HVOF coatings can be formed
23 nearly 100% dense, with at a porosity of about 0.5%.

24

25 The high particle velocities obtained using the HVOF process results in relatively
26 better bonding between the coating material 12 and the substrate, as compared with
27 other coating methods such as the Conventional Plasma spray method or the

1 Chemical Vapor Deposition method. However, the HVOF process also forms a bond
2 between the coating material 12 and the substrate that occurs primarily through
3 mechanical adhesion at a bonding interface. As will be described below, in
4 accordance with the present invention this mechanical bond is converted to a
5 metallurgical bond by creating a diffusion bond between the coating material 12 and
6 the workpiece substrate. The diffusion bond does not have the interface boundary
7 which is usually the site of failure.

8
9 The diffusion bond is created by subjecting the coated workpiece substrate to a hot
10 isostatic pressing (HIP) treatment. The appropriate hot isostatic pressing treatment
11 parameters are selected depending on the coating, the workpiece substrate and the
12 final attributes that are desired (Step Seven). The hot isostatic pressing treatment is
13 performed on the coated workpiece substrate to obtain a metal product having the
14 desired finished dimensions and diffusion bonding between the coating material 12
15 and the workpiece substrate (Step Eight).

16
17 By proper formation of the workpiece substrate, the final dimensions of the finished
18 workpiece product can be accurately achieved through the precise control of the build
19 up of coating material 12 when the HVOF plasma spray process is performed.

20 Alternatively, the HIP treated and HVOF coated workpiece substrate may be
21 machined to final dimensions as necessary (Step Nine).

22
23 HIP treatment is conventionally used in the densification of cast metal components
24 and as a diffusion bonding technique for consolidating powder metals. In the HIP
25 treatment process, a part to be treated is raised to a high temperature and isostatic
26 pressure. Typically, the part is heated to 0.6 - 0.8 times the melting point of the
27 material comprising the part, and subjected to pressures on the order of 0.2 to 0.5

1 times the yield strength of the material. Pressurization is achieved by pumping an
2 inert gas, such as Argon, into a pressure vessel 14. Within the pressure vessel 14 is a
3 high temperature furnace, which heats the gas to the desired temperature. The
4 temperature and pressure is held for a set length of time, and then the gas is cooled
5 and vented.

6
7 The HIP treatment process is used to produce near-net shaped components, reducing
8 or eliminating the need for subsequent machining operations. Further, by precise
9 control of the temperature, pressure and time of a HIP treatment schedule a particular
10 microstructure for the treated part can be obtained.

11
12 In accordance with the present invention, the HIP treatment process is performed on a
13 HVOF coated substrate to convert the adhesion bond, which is merely a relatively
14 weaker mechanical bond, to a diffusion bond, which is a relatively stronger
15 metallurgical bond. In accordance with the present invention, an HVOF coating
16 process is used to apply the coating material 12 having sufficient density to
17 effectively undergo the densification changes that occur during the HIP process. A
18 sintering heat treatment step may be performed improve the density of the coating
19 material and prevent gas entrapment during the hot isostatic pressing treatment. If the
20 coating material 12 and the workpiece substrate are comprised of the same metal
21 composition, then the diffusion bonding results in a particularly seamless transition
22 between the substrate and the coating.

23
24 As shown in Figures 2(a) through 2(d), the inventive method can be used for forming
25 a metal product having a wear resistant surface. Figure 2(a) is a schematic view
26 showing a tool substrate 10 provided in accordance with the inventive method of
27 forming metal components having a wear resistant coating. The inventive method can

1 be employed to produce, for example, a long lasting cutting tool from a relatively
2 inexpensive cutting tool substrate 10.

3

4 In accordance with this aspect of the invention, a workpiece substrate is formed to
5 near-finished dimensions. The tool substrate 10 may be a drill bit, end mill, lathe tool
6 bit, saw blade, planer knives, cutting tool inserts, or other cutting tool part. The
7 substrate may, alternatively, be something other than a tool. For example, ice skate
8 blades and snow ski edges may be treated in accordance with the present invention to
9 obtain a long wearing edge. Kitchen knives may be treated in accordance with the
10 present invention to reduce or even eliminate the need for constant sharpening.

11 Further, products such as pen tips and fishing hooks may be treated in accordance
12 with the present invention so as to benefit from long lasting durability. Nearly any
13 metal component that could benefit from a longer wearing, dense surface structure
14 might be a candidate from the present invention. For example, steam turbine erosion
15 shields, fly ash fan blades, power plant conveyors, are all subjected to wear and/or
16 surface erosion forces. The present invention can be used to provide the protective
17 surface characteristics, as described herein, that enhance the effectiveness of products
18 such as these.

19

20 Figure 2(b) is a schematic view of the tool substrate 10 having a wear resistant
21 coating applied using an HVOF thermal spray process in accordance with the
22 inventive method. A high-density coating process, such as a hyper velocity oxy-fuel
23 thermal spray process, is performed to coat the workpiece substrate 10 with a wear
24 resistant coating material 12 using, for example, an HVOF nozzle. The coating
25 material 12 is built-up to a thickness that is effective to obtain desired finished
26 dimensions after performing a hot isostatic pressing treatment.

27

1 Figure 2(c) is a schematic view of the HVOF spray coated tool substrate 10
2 undergoing a HIP treatment process in a HIP vessel 14. The hot isostatic pressing
3 treatment is performed on the coated workpiece substrate to obtain a metal product
4 having the desired finished dimensions and diffusion bonding between the coating
5 material 12 and the workpiece substrate.

6
7 Figure 2(d) is a schematic view of the final HVOF spray coated and HIP treated tool
8 having a wear resistant coating layer diffusion bonded to the tool substrate 10. In
9 accordance with the present invention the mechanical bond formed between the
10 parent substrate and the applied coating is converted to a metallurgical bond by
11 creating a diffusion bond between the coating material 12 and the parent substrate.
12 The diffusion bond does not have the interface boundary which is usually the site of
13 failure, thus a superior product is obtained that has desired surface properties, such as
14 wear resistance, color, smoothness, texture, etc. These surface properties do not end
15 abruptly at a bonding interface (as is the case of conventional coated or brazed
16 products), but rather remain present to a continuously varying degree from the
17 product surface to the parent metal. A cutting edge can be put on the tool surface by
18 conventional sharpening techniques taking care not to remove more of the diffusion
19 bonded coating than is necessary.

20
21 Figures 3(a) through 3(e) illustrate the present inventive method employed for
22 forming a cast metal product having predetermined dimensions and surface
23 characteristics. Figure 3(a) is a schematic perspective view of a cast metal workpiece
24 substrate undergoing a machining operation. As shown in Figure 3(a), the cast metal
25 workpiece is machined, if necessary, to near-finished dimensions. Figure 3(b) is a
26 schematic perspective view of the machined cast metal component.

1 A high-density coating process, such as a hyper velocity oxy-fuel thermal spray
2 process, is performed to coat the workpiece substrate with a coating material 12.
3 Figure 3(c) is a schematic perspective view of the machined cast metal component
4 having a coating applied using an HVOF thermal spray process. The coating material
5 12 is built-up to a thickness effective to obtain desired finished dimensions after
6 performing a hot isostatic pressing treatment. Figure 3(d) is a schematic perspective
7 view of the HVOF spray coated machined cast metal component undergoing a HIP
8 treatment process in a HIP vessel 14. The hot isostatic pressing treatment is
9 performed on the coated workpiece substrate to obtain a metal product having the
10 desired finished dimensions and diffusion bonding between the coating material 12
11 and the workpiece substrate. Figure 3(e) is a schematic perspective view of the final
12 HVOF spray coated and HIP treated machined cast metal product having a coating
13 layer diffusion bonded to the machined cast metal component.

14

15 Figure 4 is a flow chart showing the steps of the inventive method of repairing a
16 turbine engine part. The present inventive method can be used for repairing a turbine
17 engine part 18, such as a blade or vane. In accordance with this aspect of the
18 invention a turbine engine part 18, which is comprised of a metal or metal alloy, is
19 first cleaned (Step One). If necessary, eroded portions of the turbine engine part 18
20 are welded using a weld material comprised of the same metal or metal alloy as the
21 parent or original metal engine part (Step Two). The welding operation is performed
22 to build up heavily damaged or eroded portions of the turbine engine part 18. If the
23 part is not heavily damaged, the welding operation may be obviated.

24

25 The welding operation will typically produce weld witness lines. The weld witness
26 lines are ground flush to prevent blast material from becoming entrapped in the weld
27 witness lines (Step Three). Portions of the engine part that are not to be HVOF

1 sprayed are masked (Step Four), and the engine part is again cleaned in preparation
2 for HVOF spraying (Step Five). HVOF plasma spraying of the unmasked portions of
3 the engine part is performed (Step Six). The HVOF plasma spray material (coating
4 material 12) is comprised of the same metal alloy as the parent or original metal
5 engine part. The HVOF plasma spray material is applied so as to build up a cordal
6 dimension of the engine part to a thickness greater than the thickness of an original
7 cordal dimension of the engine part. A sintering heat treatment process may be
8 performed to further densify the coating material. A hot isostatic pressing (HIP)
9 treatment if performed on the coated engine part to densify the coating material 12, to
10 create a diffusion bond between the coating material 12 and the parent and weld
11 material, and to eliminate voids between the turbine engine part 18, the weld material
12 and the coated material (Step Seven). Finally, the engine part is machined, ground
13 and/or polished to the original cordal dimension (Step Eight).

14
15 Figure 5(a) is a schematic side view and Figure 5(b) is a schematic cross-sectional
16 view of a worn turbine engine part 18 before undergoing the inventive method of
17 repairing a turbine engine part 18. Metal alloy components, such as gas turbine parts
18 such as blades and vanes, are often damaged during use. During operation, gas
19 turbine parts are subjected to considerable degradation from high pressure and, in the
20 case of rotating components such as blades, centrifugal force in a hot corrosive
21 atmosphere. The gas turbine parts also sustain considerable damage due to impacts
22 from foreign particles. Further, during inspection and/or repair operations the engine
23 parts are stripped of a protective diffusion coating, which usually results in the
24 reduction of some of the substrate thickness. This degradation results in a limited
25 service life for these parts. Since they are costly to produce, various conventional
26 repair methods are employed to refurbish damaged gas turbine blades and vanes.

27 However, these conventional repair methods generally require labor intensive

1 machining and welding operations that often subject the part to damaging stress.
2 Also, these conventional repair methods typically utilize low pressure plasma spray
3 for the application of a coating material 12. Conventional plasma spray coating
4 methods deposit the coating material 12 at relatively low velocity, resulting in voids
5 being formed within the coating and in a coating density typically having a porosity
6 of about 5.0%. Again, the bond between the substrate and the coating occurs
7 primarily through mechanical adhesion at a bonding interface, and if the coating is
8 subjected to sufficient shearing forces it will flake off of the workpiece substrate.
9 Further, the high porosity of the coating obtained through conventional plasma spray
10 coating make them inadequate candidates for diffusion bonding through the HIP
11 treating process described herein.

12

13 Figure 6(a) is a schematic side view and Figure 6(b) is a schematic cross-sectional
14 view of the worn turbine engine part 18 showing the worn areas 20 to be repaired
15 using the inventive method of repairing a turbine engine part 18. The area enclosed
16 by the dashed lines represent the material that has been erode or otherwise lost from
17 the original turbine engine part 18. In accordance with the present invention, this area
18 is reconstituted using the same material as the original blade and using the inventive
19 metal treatment process. The worn turbine engine part 18 (in this case, a turbine
20 blade) is first cleaned to prepare the worn surfaces for welding (see Step One, Figure
21 4).

22

23 Figure 7(a) is a schematic side view and Figure 7(b) is a schematic cross-sectional
24 view of the worn turbine engine part 18 showing the worn areas filled in with similar
25 weld material 22 in accordance with the inventive method of repairing a turbine
26 engine part 18 (see Step Two, Figure 4). In accordance with the present invention,

1 the weld material is the same as the original blade material making the bond between
2 the weld and the substrate exceptionally strong.

3

4 Figure 8(a) is a schematic side view and Figure 8(b) is a schematic cross-sectional
5 view of the welded turbine engine part 25 showing areas 24 to be built up with similar
6 coating material 12 using an HVOF spray coating process in accordance with the
7 inventive method of repairing a turbine engine part. In accordance with the present
8 invention, the coating material 12 is the same as the original blade material, again
9 making the bond between the weld and the substrate exceptionally strong.

10

11 Figure 9(a) is a schematic side view and Figure 9(b) is a schematic cross-sectional
12 view of the HVOF built up, welded turbine engine part 27 showing an area, such as
13 the vane or blade root, masked 26 before performing the HVOF spray coating process
14 in accordance with the inventive method of repairing a turbine engine part. The
15 coating material 12 is built-up to a thickness that is effective to obtain desired finished
16 dimensions after performing a hot isostatic pressing treatment (described below).

17

18 The high-density coating process may comprise performing a hyper velocity oxy-fuel
19 thermal spray process. In the case of HVOF, a fuel gas and oxygen are used to create
20 a combustion flame at 2500 to 3100°C. The combustion takes place at a very high
21 chamber pressure and a supersonic gas stream forces the coating material 12 through
22 a small-diameter barrel at very high particle velocities. The HVOF process results in
23 extremely dense, well-bonded coatings. Typically, HVOF coatings can be formed
24 nearly 100% dense, with at a porosity of about 0.5%. The high particle velocities
25 obtained using the HVOF process results in relatively better bonding between the
26 coating material 12 and the substrate, as compared with other coating methods such as
27 the conventional plasma spray method or the chemical vapor deposition method.

1 However, the HVOF process forms the bond between the coating material 12 and the
2 substrate that occurs primarily through mechanical adhesion at a bonding interface.

3 As will be described below, in accordance with the present invention this mechanical
4 bond is converted to a metallurgical bond by creating a diffusion bond between the
5 coating material 12 and the workpiece substrate. The diffusion bond does not have
6 the interface boundary which is usually the site of failure.

7

8 The diffusion bond is created by subjecting the coated workpiece substrate to a hot
9 isostatic pressing (HIP) treatment. The appropriate hot isostatic pressing treatment
10 parameters are selected depending on the coating, the workpiece substrate and the
11 final attributes that are desired. The hot isostatic pressing treatment is performed on
12 the coated workpiece substrate to obtain a metal product having the desired finished
13 dimensions and diffusion bonding between the coating material 12 and the workpiece
14 substrate.

15

16 Figure 10 is a schematic view of the HVOF built up, welded turbine engine part 27
17 undergoing a HIP treatment process in a HIP vessel 14 in accordance with the
18 inventive method of repairing a turbine engine part.

19

20 HIP treatment is conventionally used in the densification of cast metal components
21 and as a diffusion bonding technique for consolidating powder metals. In the HIP
22 treatment process, a part to be treated is raised to a high temperature and isostatic
23 pressure. Typically, the part is heated to 0.6 - 0.8 times the melting point of the
24 material comprising the part, and subjected to pressures on the order of 0.2 to 0.5
25 times the yield strength of the material. Pressurization is achieved by pumping an
26 inert gas, such as Argon, into a pressure vessel 14. Within the pressure vessel 14 is a
27 high temperature furnace, which heats the gas to the desired temperature. The

1 temperature and pressure is held for a set length of time, and then the gas is cooled
2 and vented.

3

4 The HIP treatment process is used to produce near-net shaped components, reducing
5 or eliminating the need for subsequent machining operations. Further, by precise
6 control of the temperature, pressure and time of a HIP treatment schedule a particular
7 microstructure for the treated part can be obtained.

8

9 Figure 11(a) is a schematic side view and Figure 11(b) is a schematic cross-sectional
10 view of the final HVOF spray coated and HIP repaired turbine engine part 28 having
11 a similar metal coating layer diffusion bonded to the original parent substrate and
12 welded portions in accordance with the inventive method of repairing a turbine engine
13 part. By proper formation of the workpiece substrate, the final dimensions of the
14 finished workpiece produce can be accurately achieved through the precise control of
15 the build up of coating material 12 when the HVOF plasma spray process is
16 performed. Alternatively, the HIP treated and HVOF coated workpiece substrate
17 may be machined to final dimensions as necessary (Step Eight).

18

19 An experimental test piece was prepared in accordance with the inventive method of
20 treating metal components. Photomicrographs of the test piece showed the grain
21 structure and diffusion bonding of the coating material 12 and the substrate after the
22 inventive method has been performed. The HIP treatment process was performed on
23 an HVOF coated test substrate to convert the adhesion bond between the coating and
24 the substrate, which is merely a mechanical bond, to a diffusion bond, which is a
25 metallurgical bond. In accordance with the present invention, an HVOF coating
26 process is used to apply the coating material 12 having sufficient density to
27 effectively undergo the densification changes that occur during the HIP process. In

1 the case of the test piece example, the coating material 12 and the workpiece substrate
 2 are comprised of the same metal composition. The diffusion bonding results in a
 3 transition between the substrate and the coating that has a much stronger structural
 4 integrity and wear characteristics as compared with the conventional art.

5

6 The test piece was prepared by building up coating material 12 to a thickness of
 7 approximately 0.02 inches, and the composition of the test pieces was determined at
 8 seven locations (A-G) across a cross section of the piece. The composition was found
 9 to be substantially uniform across the cross-section of the test piece, as shown in the
 10 following table.

11

Table I

12

Elemental Composition

13

(Weight %)

14 <u>Element</u>	<u>A</u>	<u>B</u>	<u>C</u>	<u>D</u>	<u>E</u>	<u>F</u>	<u>G</u>
15 Aluminum	5.4	5.2	5.5	6.2	6.3	6.4	6.5
16 Titanium	0.6	0.6	1.0	0.6	1.0	0.6	0.9
17 Chromium	12.9	13.2	14.5	12.7	11.5	13.7	14.1
18 Nickel	REM	REM	REM	REM	REM	REM	REM
19 Niobium	1.4	1.5	1.8	2.1	1.7	2.3	2.6
20 Molybdenum	3.7	4.1	3.6	3.3	3.4	3.9	3.0

21

22 A photomicrograph of the treated workpiece shows the grain structure and diffusion
 23 bonding of the coating material 12 and the substrate after the inventive method has
 24 been performed. In accordance with the present invention, the HIP treatment process
 25 is performed on a HVOF built up, welded turbine engine part to convert the adhesion

26 bond, which is merely a mechanical bond, to a diffusion bond, which is a

27 metallurgical bond. In accordance with the present invention, an HVOF coating

1 process is used to apply the coating material 12 having sufficient density to
2 effectively undergo the densification changes that occur during the HIP process. If
3 the coating material 12 and the workpiece substrate are comprised of the same metal
4 composition, then the diffusion bonding results in smooth transition between the
5 substrate and the coating. In contrast, a conventional plasma spray coating method
6 results in a relatively weak bond between the coating and the substrate. The bond is
7 primarily due to a mechanical adhesion bond that occurs relatively locally within a
8 boundary interface.

9
10 As discussed in detail above, in accordance with the present inventive method a
11 deformed gas turbine engine airfoil part can be returned to the dimensions required to
12 place the part back into useful service. A diffusion bond is created between the
13 coating material and the substrate of a repaired gas turbine engine airfoil part. This
14 diffusion bond is extremely robust and results in a repaired engine part that has the
15 appropriate mechanical properties that allow the part to be safely returned to service.
16 The inventive method of repairing a turbine engine airfoil part offers substantial
17 savings because it provides for the efficient and effective repairing of expensive
18 engine parts which otherwise might have been discarded.

19
20 As shown in Figure 13 in accordance with another aspect of the present invention, the
21 reclassification of a gas turbine engine airfoil part is obtained. The dimensional
22 differences between pre-reclassified dimensions of the buttresses of a turbine engine
23 airfoil part and desired post-reclassified dimensions of the buttresses are determined
24 (Step One). That is, the change in shape of the inner buttress and outer buttress
25 necessary to obtained a desired angular relationship between the airfoil section and
26 the buttresses is determined. Build-up thickness of coating material required to obtain
27 the desired post-reclassified dimensions of the buttresses is determined (Step Two).

1 A high-density coating process, such as HVOF, is used to coat the buttresses of the
2 turbine engine airfoil part with a coating material (Step Three). The portions of the
3 part that are not to be built up, such as the airfoil section and parts of the buttresses,
4 may be masked before applying the high-density coating. Also, some of the coated
5 surfaces of the part may need to be built up more than others. The coating material is
6 applied at least to the determined build-up thickness of coating material effective to
7 obtain the desired post-reclassification dimensions after performing a hot isostatic
8 pressing treatment, and after the selective removal of some of the original buttress
9 material and some of the built up coating material.

10

11 As discussed herein, the coating material comprises a metal alloy capable of forming
12 a diffusion bond with the substrate of the turbine engine airfoil part. After the
13 coating material is applied, the sintering heat treatment process may be performed
14 (Step Four) to prevent gas entrapment of the coating material and/or the diffusion
15 bonding area during the hot isostatic pressing process. Then, the hot isostatic pressing
16 process is performed so that the buttresses of the turbine engine airfoil part have a
17 robust diffusion bonding between the coating material and the original material of the
18 buttresses (Step Five). Having built up the appropriate dimensions of the inner
19 buttress and outer buttress, the reclassification of the part is obtained by selectively
20 removing the original buttress material and, if necessary, some of the built up material
21 until the angular relationship between the airfoil section and the inner and outer
22 buttresses is obtained (Step Six). The material can be removed through milling,
23 grinding, or other suitable and well known machining operations. Further, to
24 facilitate obtaining the correct dimensions the centerline position of the airfoil part
25 can be located and held by mounting the part in a suitable holding fixture when
26 machining the buttresses.

27

1 The fixture may be so constructed so that a vane that has at least a minimum amount
2 of material built up on its buttresses can be machined and reclassified. In this case, it
3 may not be necessary to determine the dimensional differences or the required build-
4 up thickness. Rather, the inventive high density coating and HIPing process (and, if
5 needed sintering) can be performed to build up at least the minimum amount of
6 material diffusion bonded to the buttresses. Then, the vane is placed in the fixture and
7 the excess material (both original buttress material and the built-up material) is
8 machined until the buttresses have been reshaped and the vane reclassified as
9 intended or restored to original.

10

11 The class of a turbine engine vane is defined by the angular relationship between the
12 airfoil section and the inner and outer buttresses. The inventive recast process is
13 utilized to change or restore the original class of a turbine engine airfoil part by
14 building up sufficient material on the inner buttress and the outer buttress so that the
15 buttresses can then be machined to create the desired angles α and α' (shown in
16 Figures 14(b) and 14(c)) and reclassify the vane.

17

18 All buttresses are dimensionally the same and all airfoils are dimensionally the same
19 for all classes of vanes. In accordance with the present invention, the airfoil centerline
20 position is held by mounting the vane in a fixture, and the buttresses are machined to
21 obtained to desired reclassification parameters.

22

23 The class of a turbine engine vane 20 is defined by the angular relationship between
24 the airfoil section 22 and the inner buttress 24 and outer buttress 26. The inventive
25 recast process is utilized to change or restore the original class of a turbine engine

26 airfoil part by building up sufficient material on the inner buttress 24 and the outer

1 buttress 26 so that the buttresses 24, 26 can then be machined to create the desired
2 angles α and α' (shown in Figures 14(b) and 14(c)) and reclassify the vane 20.

3

4 All buttresses 24, 26 are dimensionally the same and all airfoils are dimensionally the
5 same for all classes of vanes. In accordance with the present invention, the airfoil
6 centerline position is held by mounting the vane 20 in a fixture, and the buttresses 24,
7 26 are machined to obtained to desired reclassification parameters.

8

9 Figure 14(a) is a front view of a vane 20 from a gas turbine engine showing the airfoil
10 section 22, the outer buttress 26 and the inner buttress 24. In accordance with this
11 aspect of the invention, it is first determined what dimensions of the inner buttress 24
12 and outer buttress 26 need to be adjusted in order to obtain the desired reclassification
13 of the vane 20. Having determined the dimensional differences between the pre-
14 reclassified buttresses 24, 26 and the post-reclassified buttresses 24, 26, it is next
15 determine how much material must be added, and where the material must be added
16 so that the buttresses 24, 26 can be reshaped.

17

18 Figure 14(b) is a partial top view showing the outer buttress 26 and angle α indicating
19 the angular relationship between the airfoil section 22 and the outer buttress 26 and

20 Figure 14(c) is a partial bottom view showing the inner buttress 24 and angle α'
21 indicating the angular relationship between the airfoil section 22 and the inner
22 buttress 24. In accordance with the present invention, the vane 20 is reclassified by
23 changing the shape of the buttresses 24, 26 so that the angles α and α' are changed
24 resulting in a changed angle of attack of the airfoil section 22, and thus
25 reclassification of the vane 20.

26

1 Figure 14(d) is a partial left-side view showing the leading edge foot 28 of the inner
2 buttress 24 and the outer foot front face 30 of a buttress rail 32 of the outer buttress 26
3 and Figure 14(e) is a partial right-side view showing the trailing edge foot 34 of the
4 inner buttress 24 and the other buttress rail 32 of the outer buttress 26. In accordance
5 with the present invention, the surfaces of the buttresses 24, 26, such as the leading
6 edge foot 28, center log 36, trailing edge foot 34 (inner buttress 24), and the outer foot
7 front face 30 and buttress rails 32 (outer buttress 26) are selectively built up and
8 machined so that the angle of attack of the airfoil section 22 is adjusted. The build up
9 of material on the buttresses 24, 26 may be uniform, and then the buttresses 24, 26
10 machined to selectively remove portions of the original substrate and portions of the
11 build up material. To reduce machine costs, the surfaces of the original buttresses 24,
12 26 that are going to be machined may be masked before the buildup material is
13 applied. In this case, the buildup material will not have to be later machined along
14 with the original substrate to reshape the buttresses 24, 26 24, 26.

15

16 A fixture for holding the vane 20 during the machining operation(s) may be so
17 constructed so that the vane 20 having at least a minimum amount of material built up
18 on its buttresses 24, 26 can be machined and reclassified. In this case, it may not be
19 necessary to determine the dimensional differences or the required build-up thickness.

20 Rather, the inventive high density coating and HIPing process (and, if needed
21 sintering and other processes described herein) can be performed to build up at least
22 the minimum amount of material diffusion bonded to the buttresses 24, 26 24, 26.

23 Then, the vane 20 is placed in the fixture and the excess material (both original
24 buttress material and the built-up material) is machined until the buttresses 24, 26
25 have been reshaped and the vane reclassified as intended.

26

1 The resulting reclassified vane has inner and outer buttresses with the mechanical
2 properties required for safe return to active service in an operating gas turbine engine.
3 The diffusion bonding between the applied coating material built up on the buttresses
4 and the original buttress substrate ensures, as substantiated by the test results
5 discussed herein, that the reclassified vane can be safely returned to active service.

6
7 With respect to the above description, it is realized that the optimum dimensional
8 relationships for parts of the invention, including variations in size, materials, shape,
9 form, function, and manner of operation, assembly and use, are deemed readily
10 apparent and obvious to one skilled in the art. All equivalent relationships to those
11 illustrated in the drawings and described in the specification are intended to be
12 encompassed by the present invention.

13
14 Therefore, the foregoing is considered as illustrative only of the principles of the
15 invention. Further, since numerous modifications and changes will readily occur to
16 those skilled in the art, it is not desired to limit the invention to the exact construction
17 and operation shown and described. Accordingly, all suitable modifications and
18 equivalents may be resorted to, falling within the scope of the invention.

1 **Claims:**

2 1. A method of repairing a turbine engine airfoil part, characterized by the steps of:
3 determining dimensional differences between pre-repaired dimensions of a turbine
4 engine airfoil part and desired post-repair dimensions of the turbine engine airfoil
5 part, the turbine engine airfoil part having a metal alloy substrate; determining a
6 build-up thickness of coating material required to obtain the desired post-repair
7 dimensions of the airfoil part; performing a high-density coating process to coat the
8 turbine engine airfoil part substrate with a coating material to build-up a thickness of
9 coating material effective to obtain desired finished dimensions after performing a
10 sintering heat treatment process and a hot isostatic pressing treatment; performing the
11 sintering heat treatment on the turbine engine airfoil part to densify the coating
12 material; and then performing the hot isostatic pressing treatment to obtain a post-
13 repair turbine engine airfoil part having the desired post-repair dimensions and having
14 diffusion bonding between the coating material and the turbine engine airfoil
15 substrate.

16

17 2) A method of repairing a turbine engine airfoil part according to claim 1; further
18 comprising the step of removing a protective coating from the turbine engine airfoil
19 part prior to performing the high-density coating process.

20

21 3) A method of repairing a turbine engine airfoil part according to claim 2; wherein
22 the metal alloy substrate of the turbine engine airfoil part comprises a nickel or
23 cobalt-base superalloy; and the step of performing the high-density coating process
24 comprises performing a high-density coating process such as a hyper velocity oxy-
25 fuel thermal spray process or a detonation gun process to apply a high-density coating

26 having the same nickel or cobalt-base superalloy composition as the metal alloy
27 substrate.

1

2 4) A method of repairing a turbine engine airfoil part according to claim 3; wherein
3 the step of performing the sintering heat treatment comprises sintering at a
4 temperature at or about 1825 to 2150 degrees F for about 1/2 to 2 hours.

5

6 5) A method of repairing a turbine engine airfoil part according to claim 4; wherein
7 the step of performing the hot isostatic pressing treatment comprises hot isostatic
8 pressing at a temperature of about 2200F in about 15 KSI argon for about 4 hours.

9

10 6) A method of repairing a turbine engine airfoil part according to claim 1; wherein
11 the step of hot isostatic pressing treatment comprises the step of heating the engine
12 part to a temperature that is substantially 80% of the melting point of the metal alloy;
13 and pressurizing the engine part to a pressure substantially between 20 and 50 percent
14 of the yield strength of the metal alloy in an inert gas atmosphere.

15

16 7) A method of repairing a turbine engine airfoil part according to claim 1; wherein
17 the coating material built-up during the high-density coating process is comprised of
18 the same metal alloy as the turbine engine airfoil part substrate.

19

20 8) A method of repairing a turbine engine airfoil part according to claim 7; wherein
21 the dimensional differences between the pre-repaired dimensions of the turbine
22 engine airfoil part and the desired post-repair dimensions of the turbine engine airfoil
23 part are measured from at least one of the cordal and thickness dimensions of the
24 airfoil part.

25

- 1 9) A method of repairing a turbine engine airfoil part according to claim 8; wherein
2 the step of performing the sintering heat treatment comprises sintering at a
3 temperature at or about 1825 to 2150 degrees F for about 1/2 to 2 hours.
4
- 5 10) A method of repairing a turbine engine airfoil part according to claim 9; wherein
6 the step of performing the hot isostatic pressing treatment comprises hot isostatic
7 pressing at a temperature of about 2200F in about 15 KSI argon for about 4 hours.
8
- 9 11) A method of repairing a turbine engine airfoil part, characterized by the steps of:
10 determining dimensional differences between pre-repair cordal dimensions of a
11 turbine engine airfoil part substrate and desired post-repair cordal dimensions of the
12 turbine engine airfoil part, the post-inspection-turbine engine airfoil part being
13 comprised of a metal alloy; coating the engine part using a high-density coating
14 process and a coating material comprised of the same metal alloy so as to build up the
15 cordal dimensions of the turbine engine airfoil part to at least a desired post-repair
16 cordal dimension of the turbine engine airfoil part; performing a sintering heat
17 treatment on the turbine engine airfoil part to densify the coating material; hot
18 isostatic pressing treating the turbine engine airfoil part to produce diffusion bonding
19 between the turbine engine airfoil part and the coating material.
20
- 21 12) A method of repairing a turbine engine airfoil part according to claim 11; further
22 comprising the steps of welding eroded portions of the turbine engine airfoil part
23 using a weld material comprised of the same metal alloy, the welding process
24 producing weld witness lines; grinding flush the weld witness lines to prevent blast
25 material from becoming entrapped in the weld witness lines; masking portions of the
26 turbine engine airfoil part that are not to be coated in the high-density coating process;

1 and selectively removing portions of at least one of the weld material and the HVOF
2 spray material to obtain the desired cordal dimension of the turbine engine airfoil part.

3

4 13) A method of repairing a turbine engine airfoil part according to claim 11; wherein
5 the post inspection turbine engine airfoil part comprises a non-rotating engine part
6 having a superalloy substrate and the coating material has the same alloy composition
7 as the superalloy substrate.

8

9 14). A method of repairing a turbine engine airfoil part, characterized by the steps of:
10 determining dimensional differences between pre-repaired dimensions of a post-
11 inspection turbine engine airfoil part and desired post-repair dimensions of the
12 turbine engine airfoil part, the turbine engine airfoil part having a substrate comprised
13 of a superalloy; determining a build-up thickness of coating material required to
14 obtain the desired post-repair dimensions of the turbine engine airfoil part; performing
15 a high-density coating process to coat the turbine engine airfoil part with a coating
16 material to build-up a thickness of coating material effective to obtain desired post
17 repair dimensions after performing a sintering heat treatment process and a hot
18 isostatic pressing treatment, the coating material comprising a metal alloy capable of
19 forming a diffusion bond with the substrate; performing the sintering heat treatment
20 on the turbine engine airfoil part to densify the coating material; and then performing
21 the hot isostatic pressing process to obtain a post-repair turbine engine airfoil part
22 having the desired post-repair dimensions and having diffusion bonding between the
23 coating material and the turbine engine airfoil substrate.

24

25 15) A method of repairing a turbine engine airfoil part according to claim 14; wherein

26 the post inspection turbine engine airfoil part comprises a non-rotating engine part

1 having a superalloy substrate and the coating material has the same alloy composition
2 as the superalloy substrate.

3

4 16) A method of repairing a turbine engine airfoil part according to claim 15;
5 wherein the step of performing the high-density coating process comprises
6 performing a high-density coating process such as a hyper velocity oxy-fuel thermal
7 spray process or a detonation gun process.

8

9 17) A method of repairing a turbine engine airfoil part according to claim 16;
10 wherein the step of hot isostatic pressing treating comprises the step of heating the
11 engine part to a temperature that is substantially 80% of the melting point of the metal
12 alloy; and pressurizing the engine part to a pressure substantially between 20 and 50
13 percent of the yield strength of the metal alloy in an inert gas atmosphere.

14

15 18) A method of repairing a turbine engine airfoil part according to claim 17;
16 wherein the dimensional differences between the pre-repaired dimensions of a turbine
17 engine airfoil part substrate and the desired post-repair dimensions of the turbine
18 engine airfoil part are measured from at least one of the chordal and length dimensions
19 of the airfoil part.

20

21 19) A method of repairing a turbine engine airfoil part according to claim 14;
22 wherein the coating material built-up during the high-density coating process is
23 comprised of the same material as the turbine engine airfoil part substrate.

24

25 20) A method of repairing a turbine engine airfoil part according to claim 14; wherein
26 the turbine engine airfoil part comprises a rotating engine part.

27

- 1 21) A method of repairing a turbine engine airfoil part according to claim 14;
2 wherein the superalloy substrate comprises a nickel or cobalt-base superalloy.
3
- 4 22) A method of repairing a turbine engine part, characterized by the steps of:
5 cleaning a turbine engine part, the turbine engine part being comprised of a metal
6 alloy; welding eroded portions of the turbine engine part using a weld material
7 comprised of the metal alloy, the welding producing weld witness lines; grinding
8 flush the weld witness lines to prevent blast material from becoming entrapped in the
9 weld witness lines; masking portions of the engine part that are not to be HVOF
10 sprayed; recleaning the engine part in preparation for HVOF spraying; HVOF
11 spraying the engine part using a HVOF spray material comprised of the metal alloy so
12 as to build up a cordal dimension of the engine part to a thickness greater than the
13 thickness of an original cordal dimension of the engine part; sintering the engine part
14 to densify the spray material; and hot isostatic pressing treating the engine part to
15 eliminate voids between the turbine engine part, the weld material and the HVOF
16 spray material; and finishing the engine part to the original cordal dimension.
17
- 18 23) A method of repairing a turbine engine part according to claim 22; wherein the
19 step of hot isostatic pressing treating comprises the step of heating the engine part to a
20 temperature that is substantially 80% of the melting point of the metal alloy; and
21 pressurizing the engine part to a pressure substantially between 20 and 50 percent of
22 the yield strength of the metal alloy in an inert gas atmosphere.
23
- 24 24) A method of reclassifying a turbine engine airfoil part, characterized by the steps
25 of: determining the dimensional differences between pre-reclassified buttresses and
26 desired post-reclassified buttresses of a turbine engine airfoil part; applying a build-up
27 material to the buttresses; and machining the buttresses and the build-up material to

1 obtain desired dimensions of the desired post-reclassified buttresses so that the turbine
2 engine airfoil part is reclassified.

3

4 25) A method of reclassifying a turbine engine airfoil part according to claim 24;
5 wherein the step of applying the build-up material comprises performing a high-
6 density coating process to coat the buttresses with a coating material to build-up a
7 thickness of coating material effective to obtain dimensions of the desired post-
8 reclassified buttresses after performing at least one of a sintering heat treatment
9 process, a hot isostatic pressing treatment, and the machining step.

10

11 26) A method of reclassifying a turbine engine airfoil part according to claim 24;
12 further comprising the step of removing a protective coating from at least the
13 buttresses of the turbine engine airfoil part prior to performing the high-density
14 coating process.

15

16 27) A method of reclassifying a turbine engine airfoil part according to claim 26;
17 wherein the buttresses of the turbine engine airfoil part comprise a nickel or cobalt-
18 base superalloy; and the step of performing the high-density coating process
19 comprises performing a high-density coating process such as a hyper velocity oxy-
20 fuel thermal spray process or a detonation gun process to apply a high-density coating
21 having the same nickel or cobalt-base superalloy composition as the metal alloy
22 substrate.

23

24 28) A method of reclassifying a turbine engine airfoil part according to claim 25;
25 wherein the step of performing the sintering heat treatment comprises sintering at a
26 temperature at or about 1825 to 2150 degrees F for about 1/2 to 2 hours.

27

- 1 29) A method of reclassifying a turbine engine airfoil part according to claim 25;
2 wherein the step of performing the hot isostatic pressing treatment comprises hot
3 isostatic pressing at a temperature of about 2200F in about 15 KSI argon for about 4
4 hours.
5
- 6 30) A method of reclassifying a turbine engine airfoil part according to claim 24;
7 wherein the step of hot isostatic pressing treatment comprises the step of heating the
8 engine part to a temperature that is substantially 80% of the melting point of the metal
9 alloy; and pressurizing the engine part to a pressure substantially between 20 and 50
10 percent of the yield strength of the metal alloy in an inert gas atmosphere.
11
- 12 31) A method of reclassifying a turbine engine airfoil part according to claim 30;
13 wherein the coating material built-up during the high-density coating process is
14 comprised of the same metal alloy as the buttresses.
15
16

1 of 12

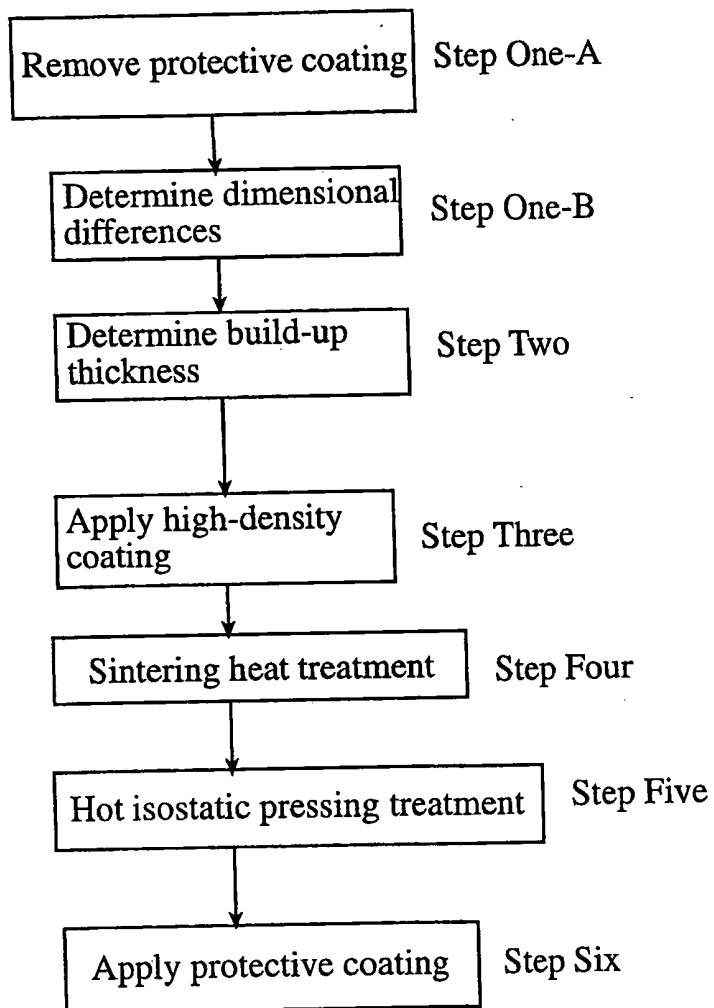
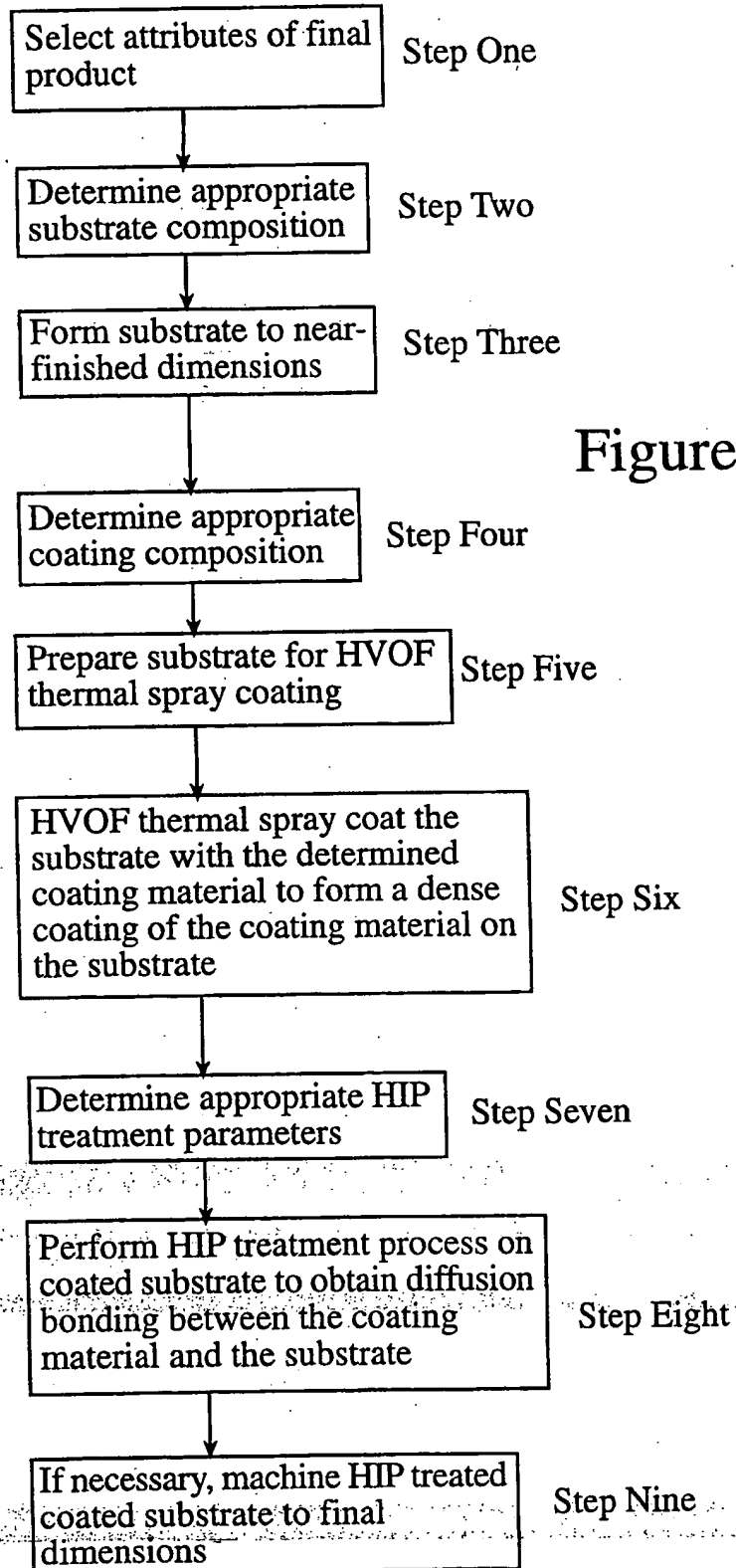


Figure 1(a)

2 of 12



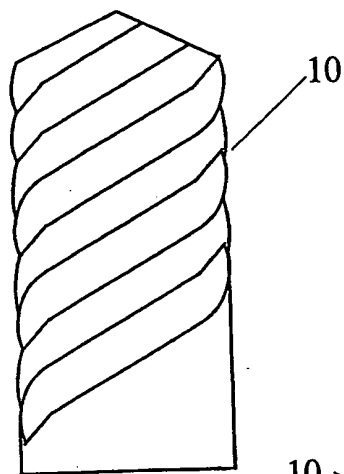


Figure 2(a)

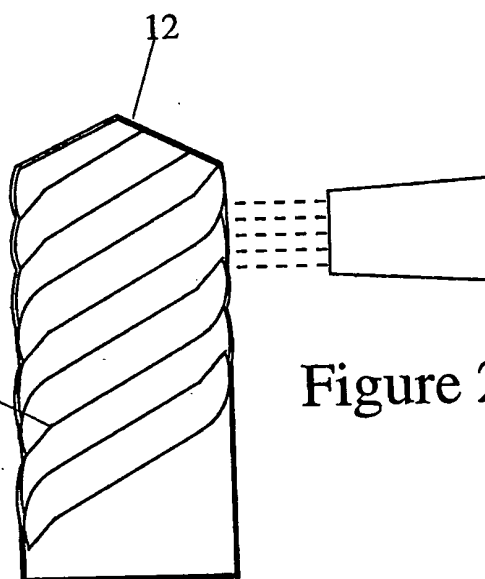


Figure 2(b)

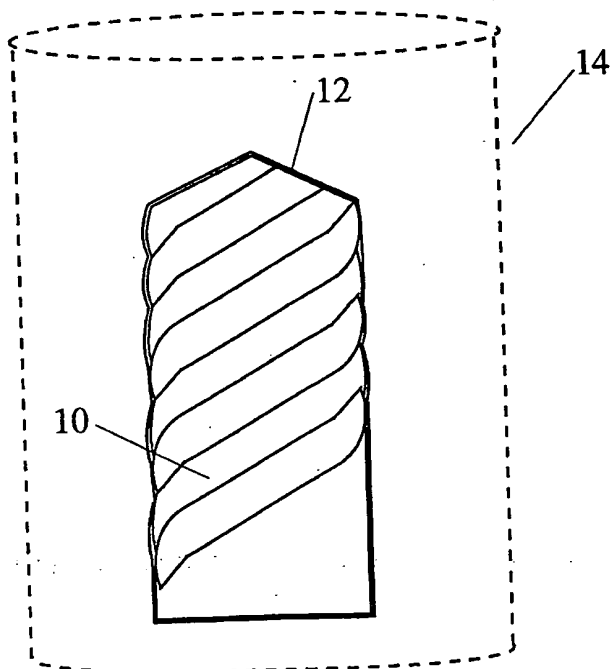


Figure 2(c)

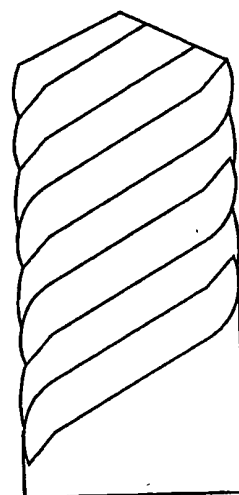


Figure 2(d)

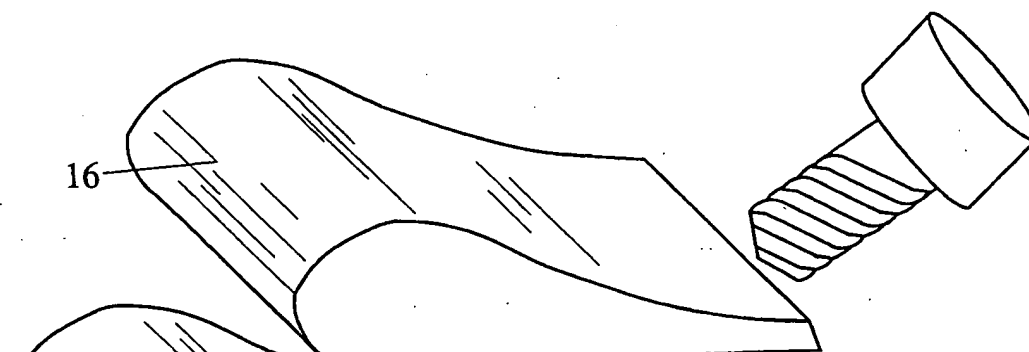


Figure 3(a)



Figure 3(b)

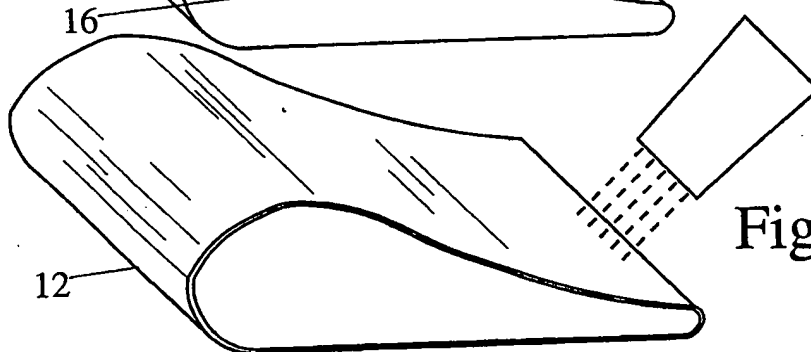


Figure 3(c)

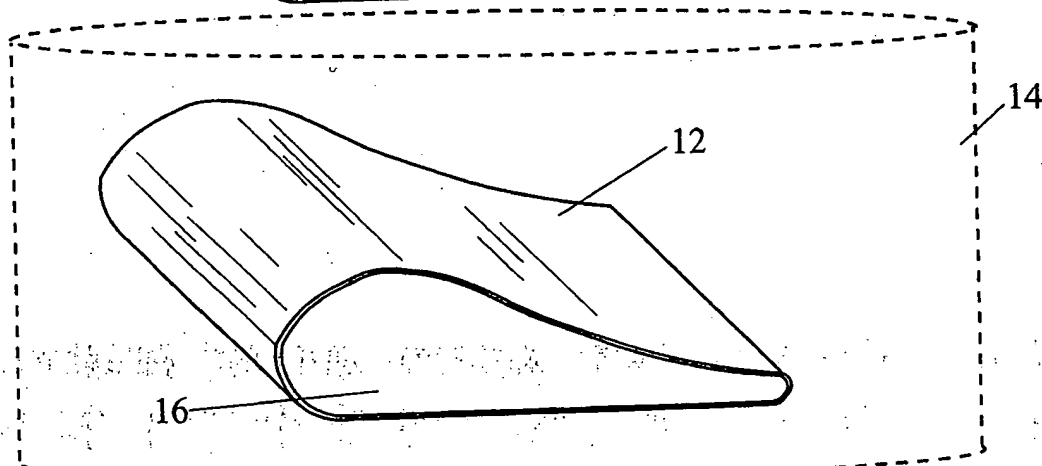


Figure 3(d)

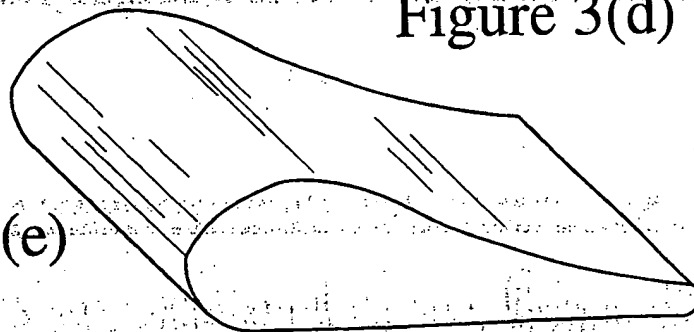
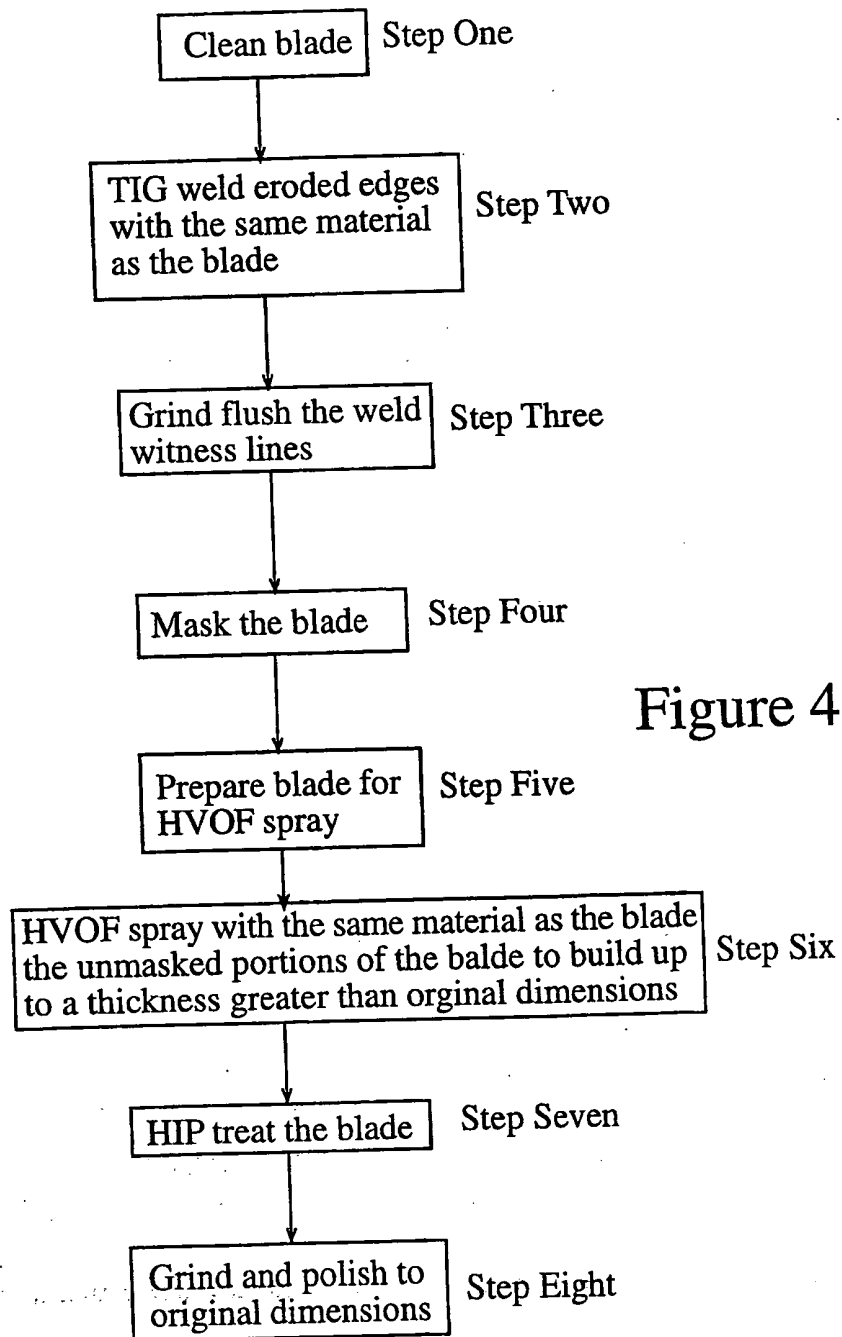


Figure 3(e)

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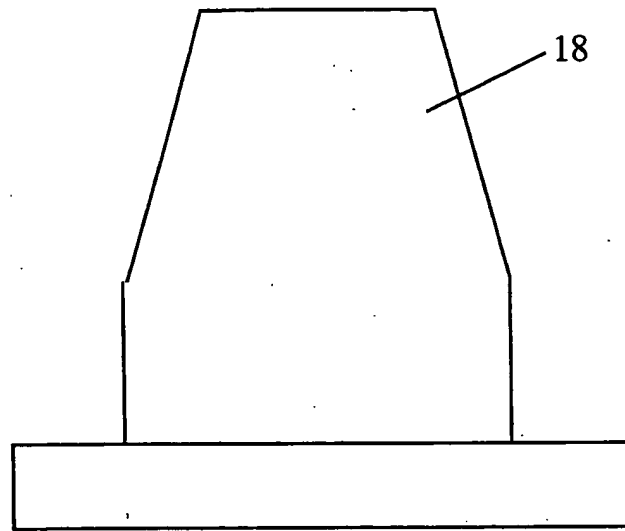


Figure 5(a)

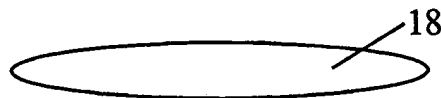


Figure 5(b)

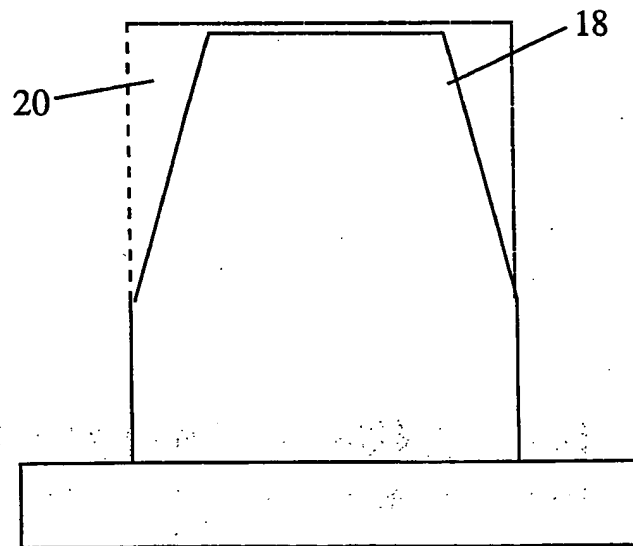


Figure 6(a)

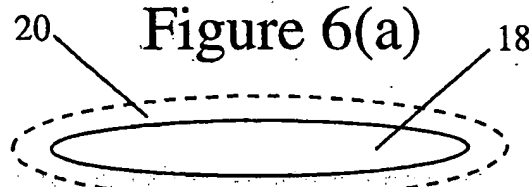


Figure 6(b)

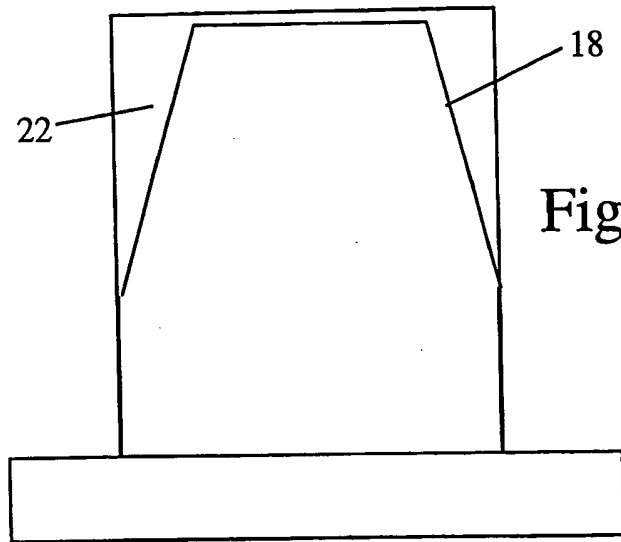


Figure 7(a)



Figure 7(b)

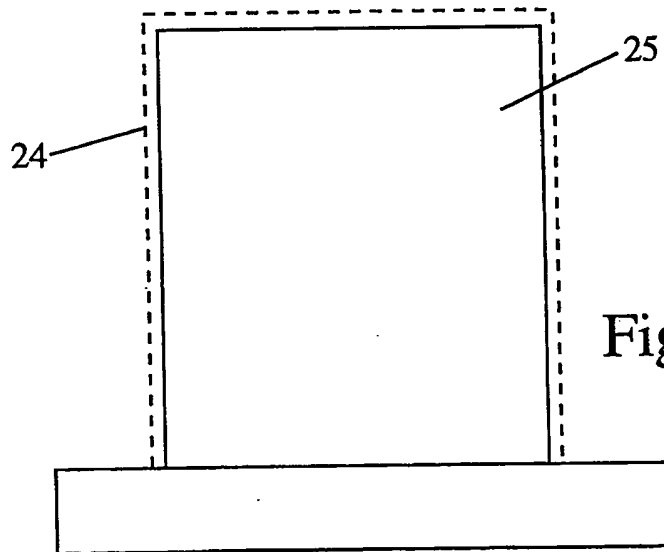


Figure 8(a)



Figure 8(b)

8 of 12

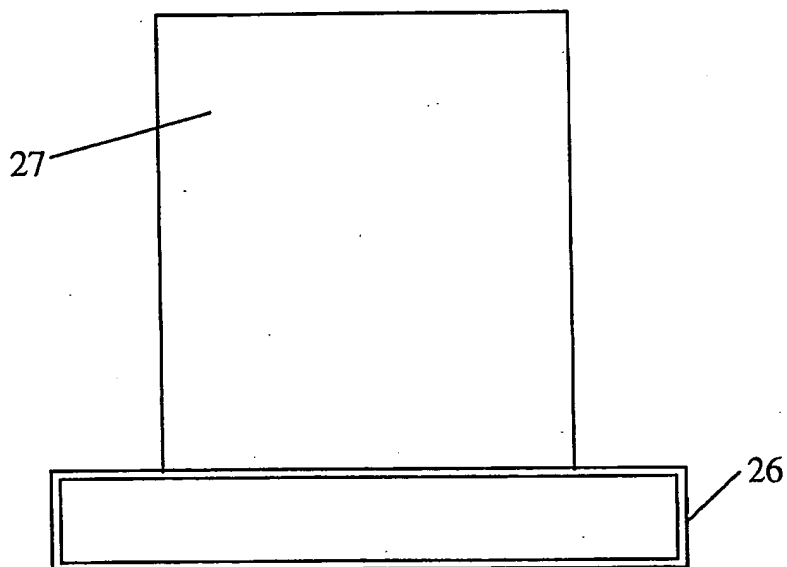


Figure 9(a)

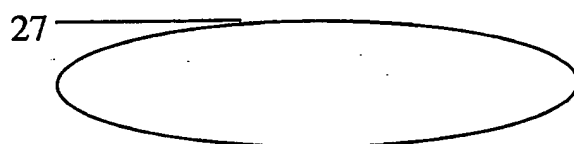


Figure 9(b)

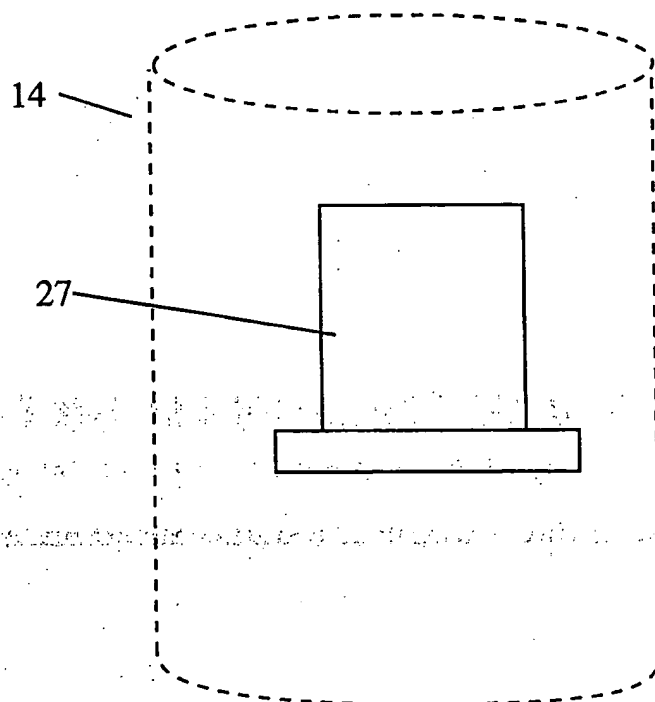


Figure 10

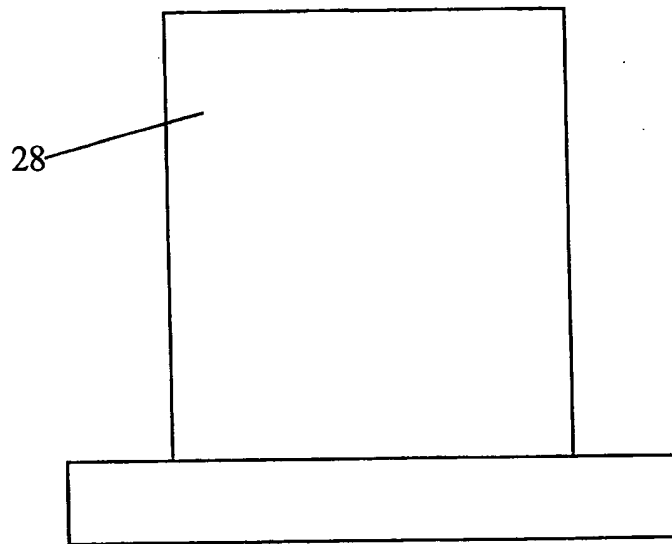


Figure 11(a)



Figure 11(b)

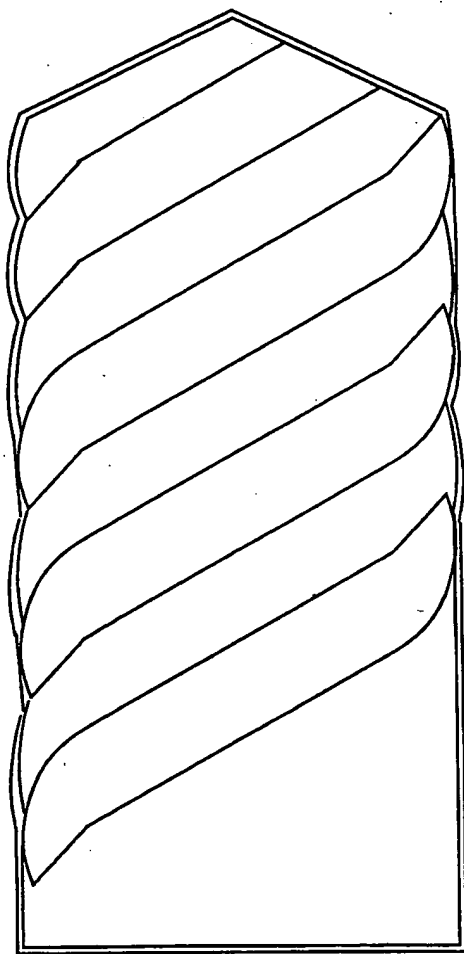


Figure 12(a)
Prior Art

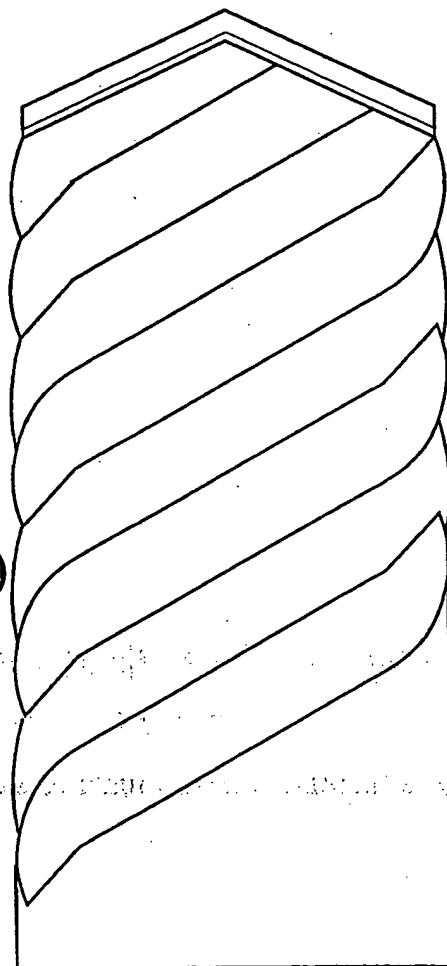


Figure 12(b)
Prior Art

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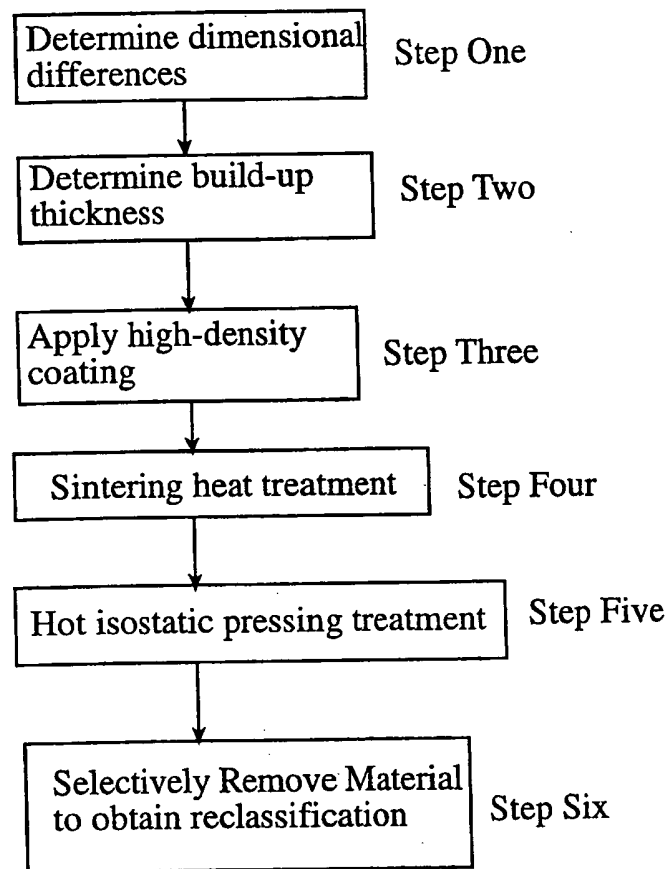


Figure 13

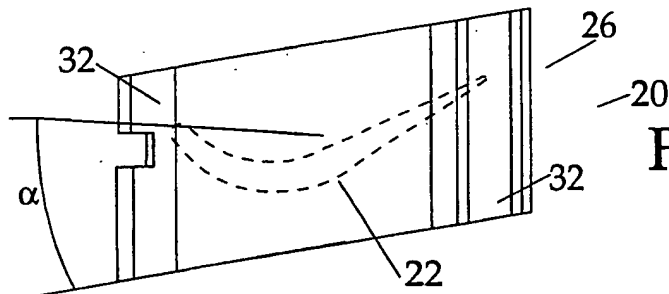


Figure 14(b)

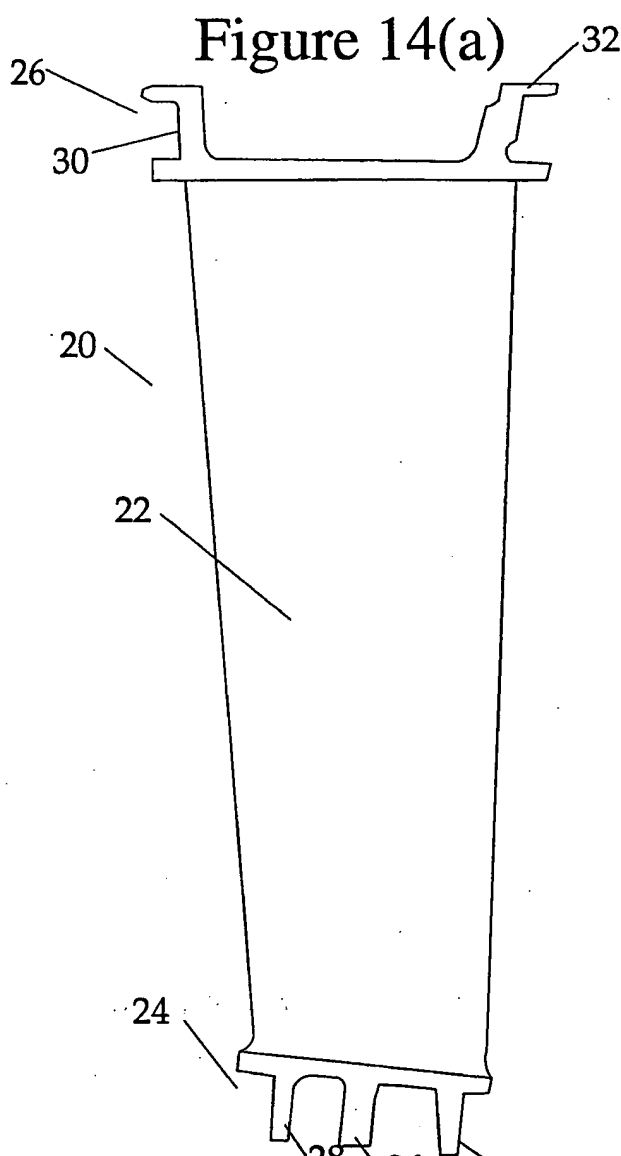


Figure 14(a)

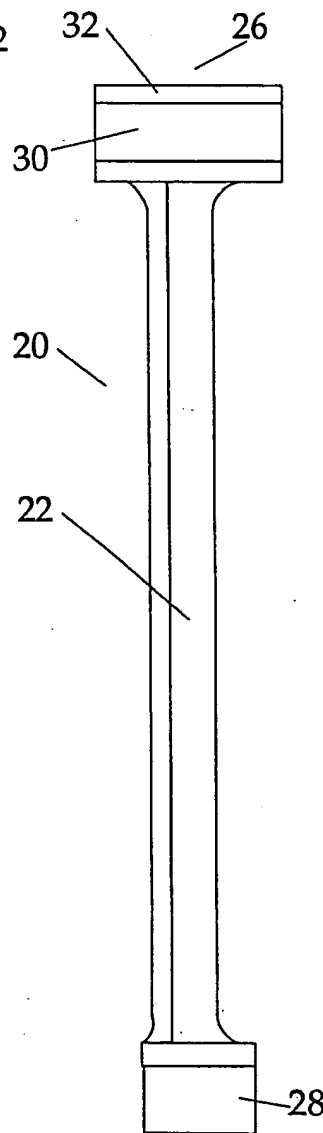


Figure 14(d)

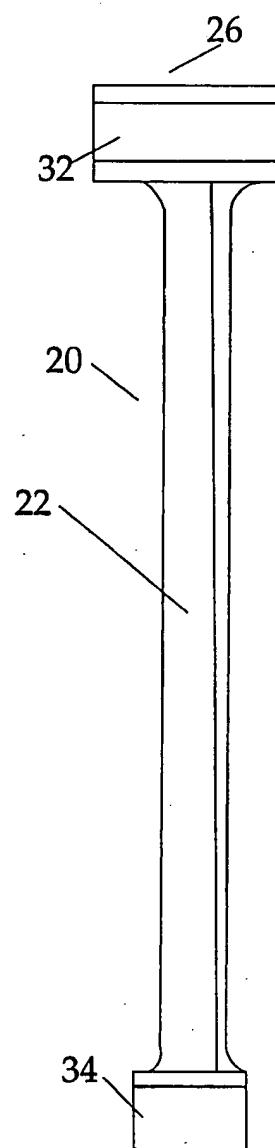


Figure 14(e)

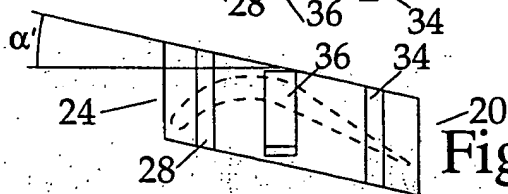


Figure 14(c)

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